Power System Analysis

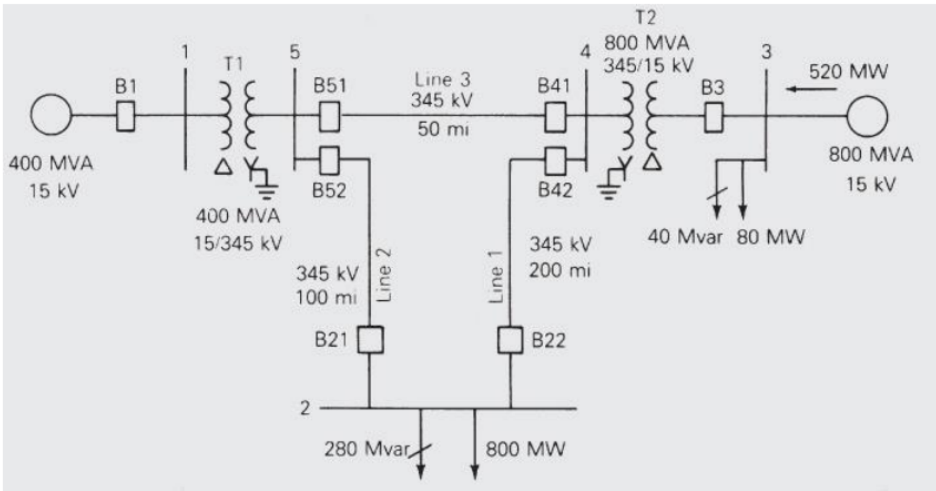
B EE478: Simulation Project #2

by

Timothy Caole **- 1920592**

Lab Due Date: 12/2/2023

1. **The single line diagram of a five-bus power system is shown below. Machine, line and transformer data are given in the following tables. Note that the neutrals of both transformers and generator 1 are solidly grounded, as indicated by a neutral reactance of zero in Tables 1 and 3. However, a neutral reactance = 0.0025 per unit is connected to the generator 2 neutral. The system is initially unloaded. Prefault voltages at all buses are 1.05 per unit.**



Single line diagram for the five-bus power system

Table 1: Synchronous machine data

Bus	X_0 per unit	$X_1 = X_d''$ per unit	X_2 per unit	Neutral Reactance X_n per unit
1	0.0125	0.045	0.045	0
3	0.005	0.0225	0.0225	0.0025

Table 2: Line data

Bus-to-Bus	X_0 per unit	$X_1 = X_2$ per unit
L1 (2-4)	0.3	0.1
L2 (2-5)	0.15	0.05
L3 (4-5)	0.075	0.025

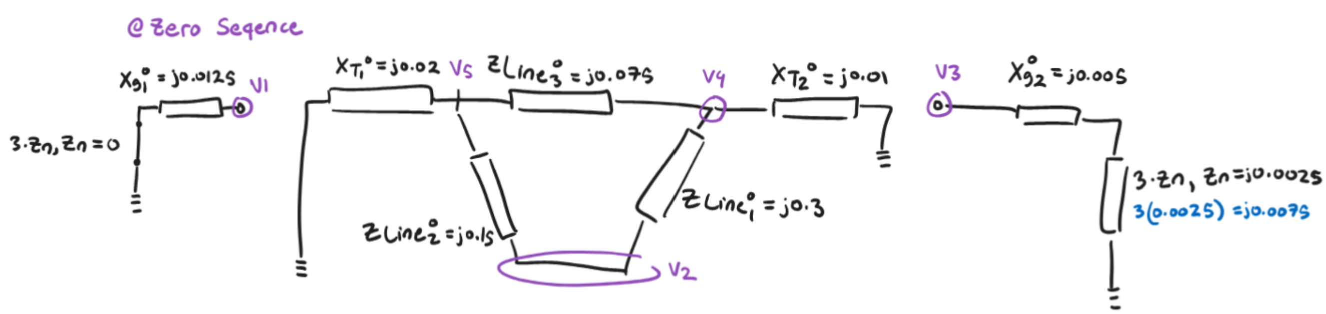
Table 3: Transformer data

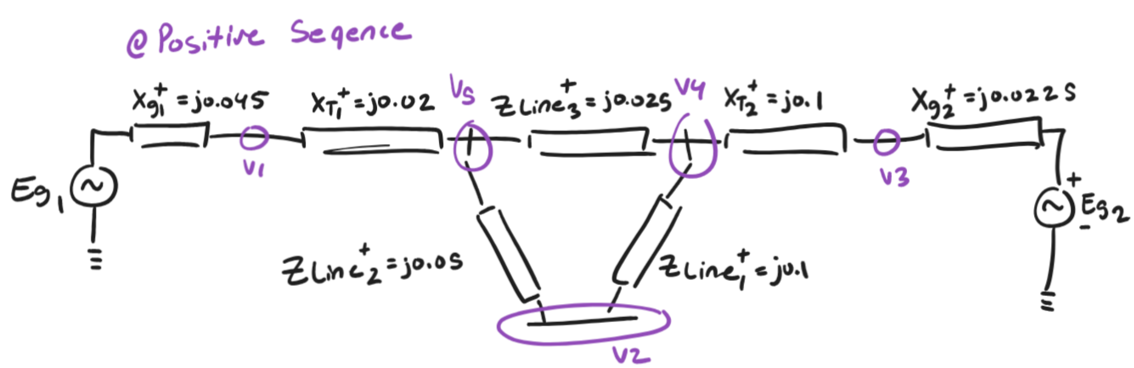
Low-Voltage (connection) bus	High-Voltage (connection) bus	Leakage Reactance Per unit	Neutral Reactance per unit
1 (Δ)	5 (Y)	0.02	0
3 (Δ)	4 (Y)	0.01	0

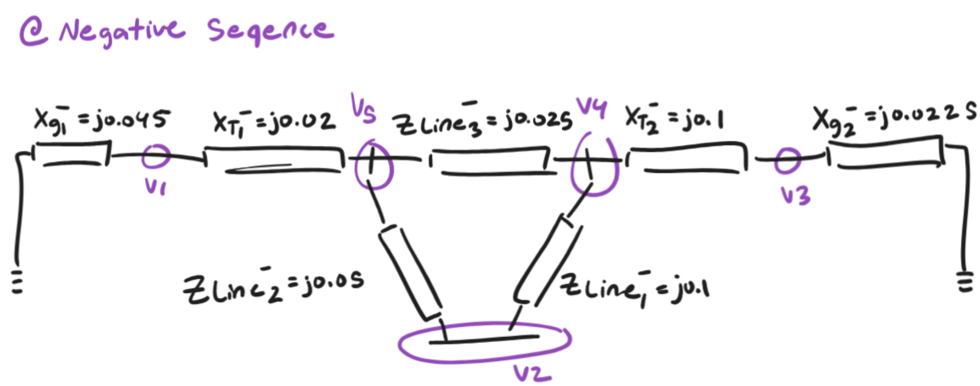
$$S_{base} = 100\ MVA$$

$$V_{base} = \begin{cases} 15\ kV\ at\ buses\ 1, 3 \\ 345\ kV\ at\ buses\ 2, 4, 5 \end{cases}$$

a) Draw the zero-, positive-, and negative-sequence reactance diagrams neglecting the transformer phase-shifts. (5 Points)





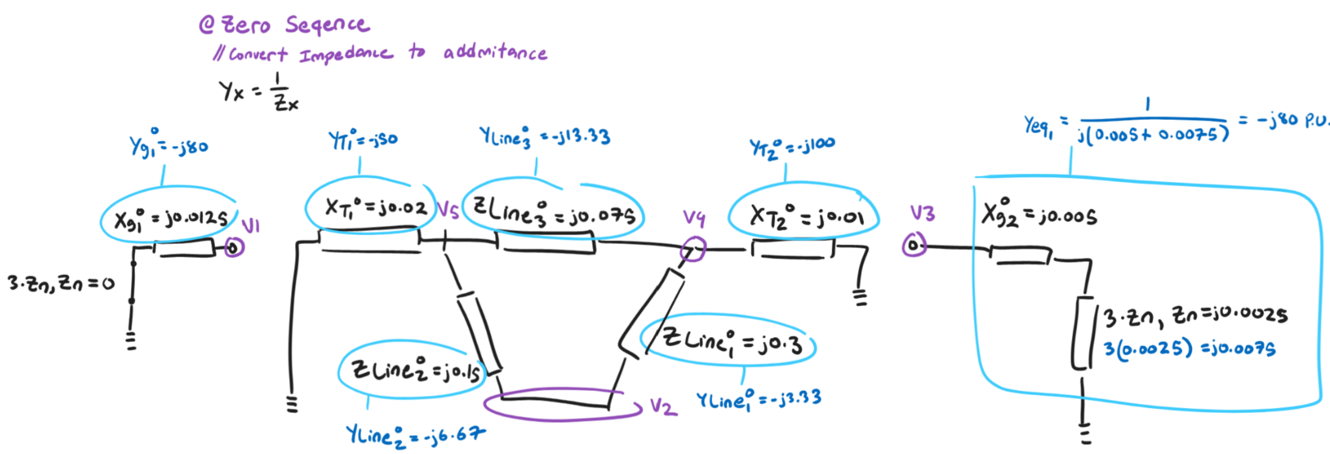


b) Calculate the bus admittance matrices for the sequence networks ($Ybus\ 0$, $Ybus\ +$, $Ybus\ -$). Clearly show how different elements of the bus admittance matrices are calculated. (5 Points)

@ Zero Seqence

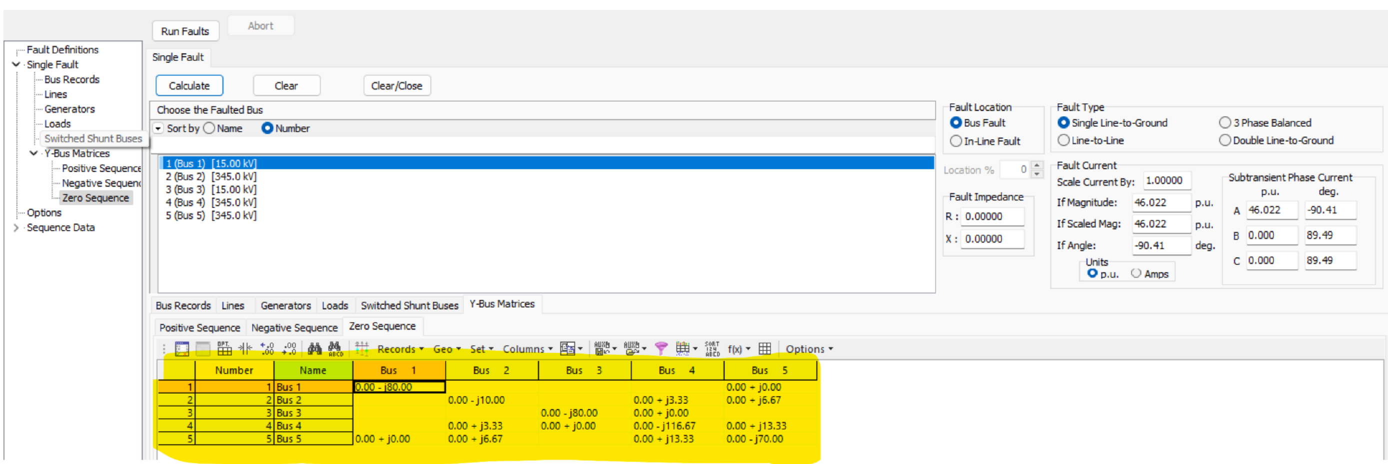
// Convert Impedance to addmitance

$Y_x = \frac{1}{Z_x}$



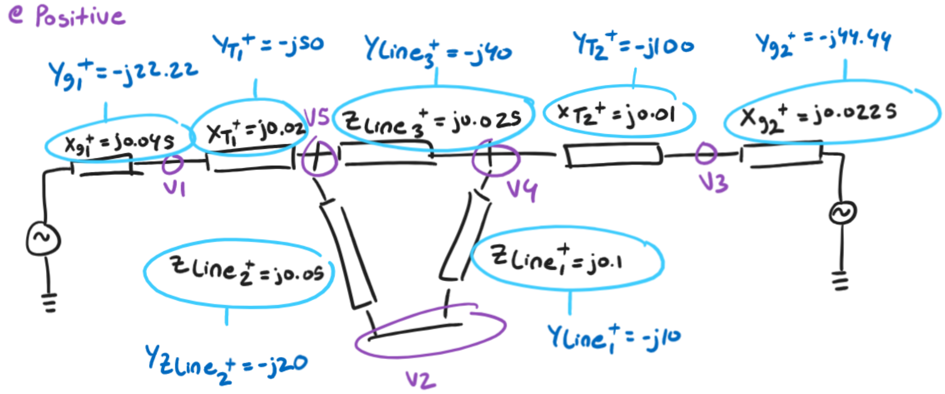
@ $Ybus^{0}$

$$Ybus^{0} = j\begin{bmatrix} -80 & 0 & 0 & 0 & 0 \\ 0 & -10 & 0 & 3.33 & 6.67 \\ 0 & 0 & -80 & 0 & 0 \\ 0 & 3.33 & 0 & -116.66 & 13.33 \\ 0 & 6.67 & 0 & 13.33 & -70 \end{bmatrix}$$



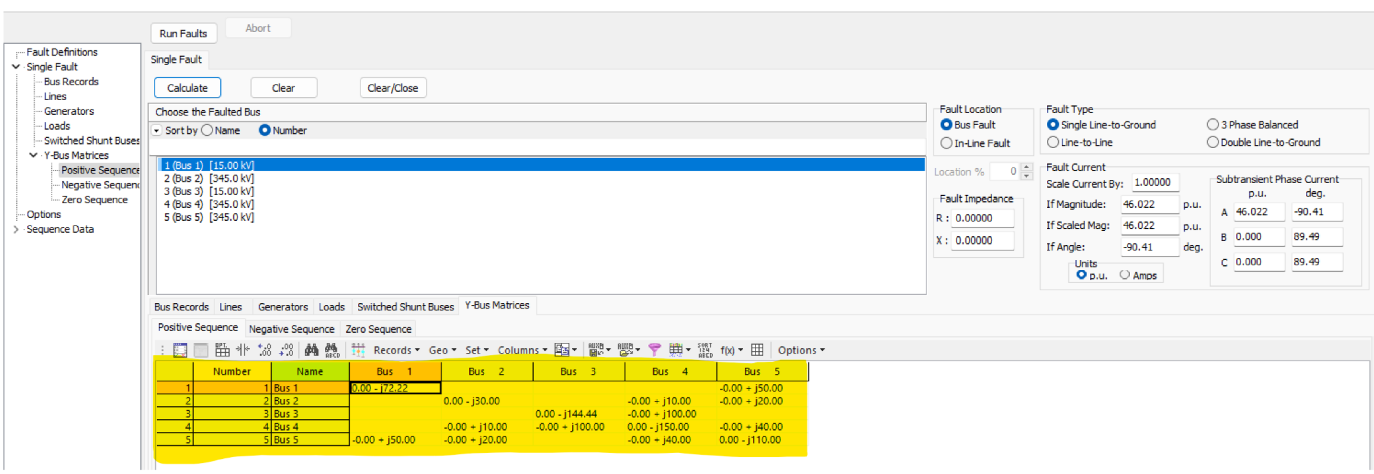
	Number	Name	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
1	1	Bus 1	0.00 - j80.00				0.00 + j0.00
2	2	Bus 2		0.00 - j10.00		0.00 + j3.33	0.00 + j6.67
3	3	Bus 3			0.00 - j80.00	0.00 + j0.00	
4	4	Bus 4		0.00 + j3.33	0.00 + j0.00	0.00 - j116.67	0.00 + j13.33
5	5	Bus 5	0.00 + j0.00	0.00 + j6.67		0.00 + j13.33	0.00 - j70.00

@ Positive



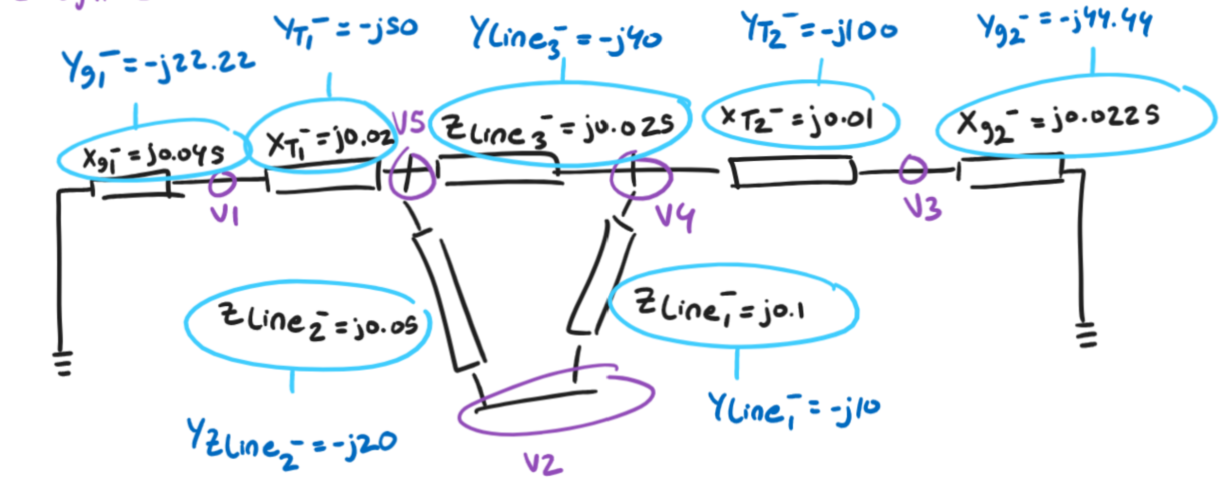
@ Y_{bus}^{+}

$$Y_{bus}^{+} = j\begin{bmatrix} -72.22 & 0 & 0 & 0 & 50 \\ 0 & -30 & 0 & 10 & 20 \\ 0 & 0 & -144.44 & 100 & 0 \\ 0 & 10 & 100 & -150 & 40 \\ 50 & 20 & 0 & 40 & -110 \end{bmatrix}$$



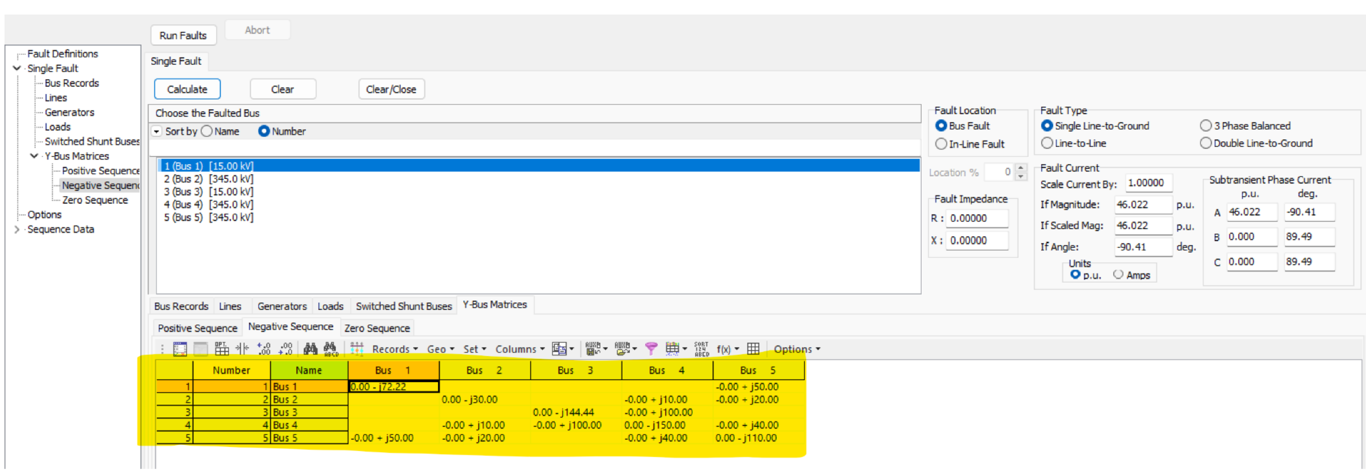
	Number	Name	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
1	1	Bus 1	0.00 - j72.22				-0.00 + j50.00
2	2	Bus 2		0.00 - j30.00		-0.00 + j10.00	-0.00 + j20.00
3	3	Bus 3			0.00 - j144.44	-0.00 + j100.00	
4	4	Bus 4		-0.00 + j10.00	-0.00 + j100.00	0.00 - j150.00	-0.00 + j40.00
5	5	Bus 5	-0.00 + j50.00	-0.00 + j20.00		-0.00 + j40.00	0.00 - j110.00

@ Negative



@ Y_{bus}^-

$$Y_{bus}^- = j\begin{bmatrix} -72.22 & 0 & 0 & 0 & 50 \\ 0 & -30 & 0 & 10 & 20 \\ 0 & 0 & -144.44 & 100 & 0 \\ 0 & 10 & 100 & -150 & 40 \\ 50 & 20 & 0 & 40 & -110 \end{bmatrix}$$



	Number	Name	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
1	1	Bus 1	0.00 - j72.22				-0.00 + j50.00
2	2	Bus 2		0.00 - j30.00		-0.00 + j10.00	-0.00 + j20.00
3	3	Bus 3			0.00 - j144.44	-0.00 + j100.00	
4	4	Bus 4		-0.00 + j10.00	-0.00 + j100.00	0.00 - j150.00	-0.00 + j40.00
5	5	Bus 5	-0.00 + j50.00	-0.00 + j20.00		-0.00 + j40.00	0.00 - j110.00

c) Use the sequence bus admittance matrices to calculate the sequence bus impedance matrices ($Zbus^{0}$, $Zbus^{+}$, $Zbus^{-}$). (5 Points) For a bolted single line-to-ground fault at bus 1, then bus 2, and so on to bus 5, do the following:

@ $Zbus^{0}$

$$Zbus^{0} = \left(Ybus^{0}\right)^{-1}$$

$$Zbus^{0} = j\begin{bmatrix} 0.0125 & 0 & 0 & 0 & 0 \\ 0 & 0.1089 & 0 & 0.0043 & 0.0112 \\ 0 & 0 & 0.0125 & 0 & 0 \\ 0 & 0.0043 & 0 & 0.0089 & 0.0021 \\ 0 & 0.0112 & 0 & 0.0021 & 0.0157 \end{bmatrix}$$

@ $Zbus^{+}$

$$Zbus^{+} = \left(Ybus^{+}\right)^{-1}$$

$$Zbus^{+} = j\begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix}$$

@ $Zbus^{-}$

$$Zbus^{-} = \left(Ybus^{-}\right)^{-1}$$

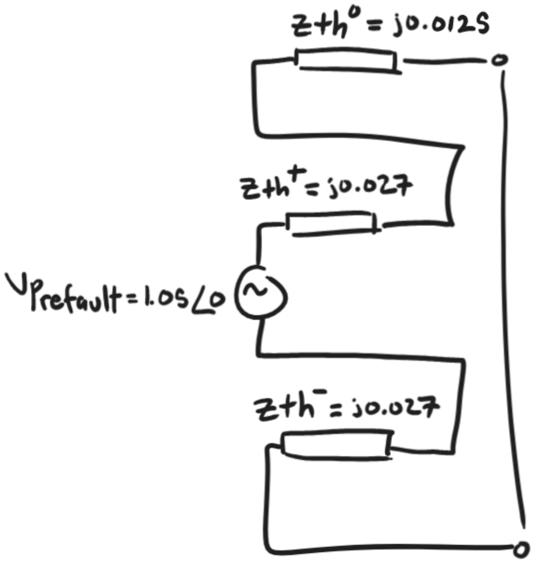
$$Zbus^{-} = j\begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix}$$

d) Use the appropriate elements of the sequence bus impedance matrices to determine the Thevenin equivalent of each sequence network as viewed form the fault bus and calculate the sequence components of the fault current for each fault. Use the calculated sequence components and the transformation matrix to calculate the phase components of the fault currents. (15 Points)

@ Bolted Single line to ground Fault @ bus 1

Condition:

$$\begin{cases} I^0 = I^+ = I^- \\ V^0 + V^+ + V^- = (3 \cdot Z_F) I^+ \end{cases}$$



$$I^0 = I^+ = I^- = \frac{V_{Prefault}}{Z_{th}^0 + Z_{th}^+ + Z_{th}^- + (3 \cdot Z_F)}$$

@ I_F - Seqence

$$I_{F_1}^0 = \frac{1.05\angle 0^\circ}{j(0.0125 + 0.027 + 0.027)}$$

$$I_{F_1}^0 = I_{F_1}^+ = I_{F_1}^- = -j15.78 \text{ P.U.}$$

@ I_F Phase

$$[I_{F\text{-}Phase}] = A \cdot [I_F \text{ Seqence}]$$

$$\begin{bmatrix} I_{F_1}^a \\ I_{F_1}^b \\ I_{F_1}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{F_1}^0 = -j15.78 \text{ P.U.} \\ I_{F_1}^+ = -j15.78 \text{ P.U.} \\ I_{F_1}^- = -j15.78 \text{ P.U.} \end{bmatrix}$$

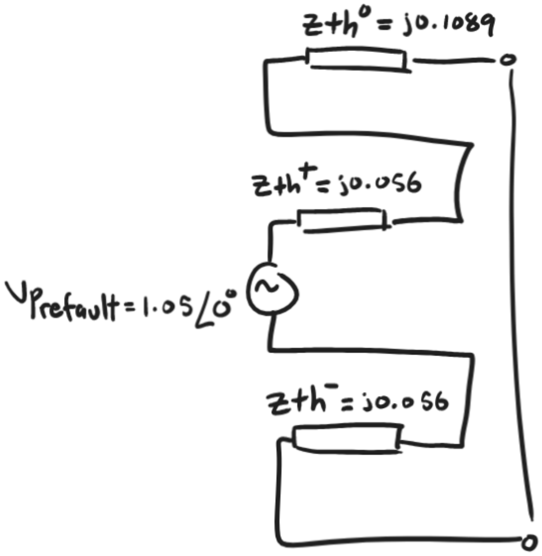
$1\angle 120^\circ$ $\quad$ $1\angle -120^\circ = 1\angle 240^\circ$

$$\begin{bmatrix} I_{F_1}^a \\ I_{F_1}^b \\ I_{F_1}^c \end{bmatrix} = \begin{bmatrix} -j47.34 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \end{bmatrix}$$

@ Bolted Single line to ground Fault @ bus 2

Condition:

$$\begin{cases} I^0 = I^+ = I^- \\ V^0 + V^+ + V^- = (3 \cdot Z_F) I^+ \end{cases}$$



$$I^0 = I^+ = I^- = \frac{V_{Prefault}}{Z_{th}^0 + Z_{th}^+ + Z_{th}^- + (3 \cdot Z_F)}$$

@ I_F - seqence

$$I_{F_2}^0 = \frac{1.05\angle 0}{j(0.1089 + 0.056 + 0.056)}$$

$$I_{F_2}^0 = I_{F_2}^+ = I_{F_2}^- = -j4.75 \text{ P.U.}$$

@ I_F Phase

$$[I_{F\text{-}Phase}] = A \cdot [I_F \text{ seqence}]$$

$$\begin{bmatrix} I_{F_2}^a \\ I_{F_2}^b \\ I_{F_2}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{F_2}^0 = -j4.75 \text{ P.U.} \\ I_{F_2}^+ = -j4.75 \text{ P.U.} \\ I_{F_2}^- = -j4.75 \text{ P.U.} \end{bmatrix}$$

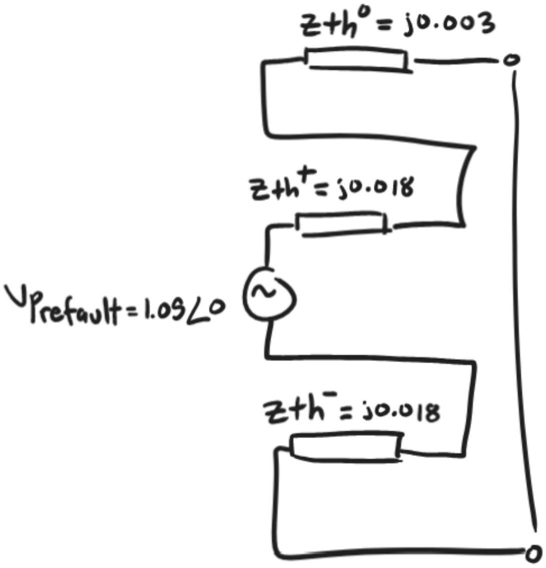
$1\angle 120°$ $\quad$ $1\angle -120° = 1\angle 240°$

$$\begin{bmatrix} I_{F_2}^a \\ I_{F_2}^b \\ I_{F_2}^c \end{bmatrix} = \begin{bmatrix} -j14.25 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \end{bmatrix}$$

@ Bolted Single line to ground Fault @ bus 3

Condition:

$$\begin{cases} I^0 = I^+ = I^- \\ V^0 + V^+ + V^- = (3 \cdot Z_F) I^+ \end{cases}$$



$$I^0 = I^+ = I^- = \frac{V_{prefault}}{Z_{th}^0 + Z_{th}^+ + Z_{th}^- + (3 \cdot Z_F)}$$

@ I_F - seqence

$$I_{F_3}^0 = \frac{1.05}{j(0.012 + 0.018 + 0.018)}$$

$$I_{F_3}^0 = I_{F_3}^+ = I_{F_3}^- = -j21.87 \text{ P.U.}$$

@ I_F Phase

$$[I_{F\text{-}phase}] = A \cdot [I_F \text{ seqence}]$$

$$\begin{bmatrix} I_{F_3}^a \\ I_{F_3}^b \\ I_{F_3}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{F_3}^0 = -j21.87 \text{ P.U.} \\ I_{F_3}^+ = -j21.87 \text{ P.U.} \\ I_{F_3}^- = -j21.87 \text{ P.U.} \end{bmatrix}$$

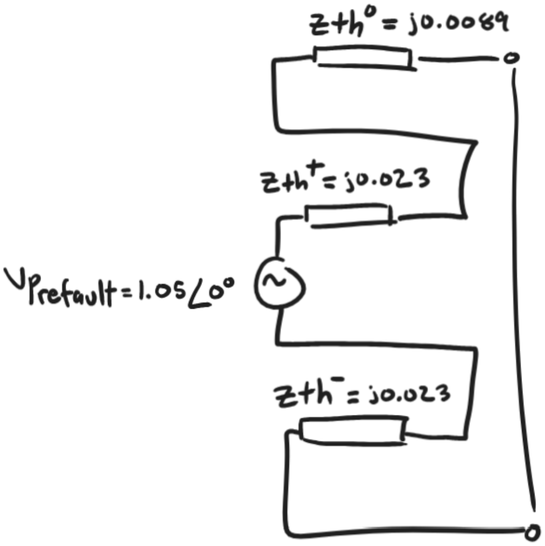
$1\angle 120°$ $\qquad$ $1\angle -120° = 1\angle 240°$

$$\begin{bmatrix} I_{F_3}^a \\ I_{F_3}^b \\ I_{F_3}^c \end{bmatrix} = \begin{bmatrix} -j65.61 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \end{bmatrix}$$

@ Bolted Single line to ground Fault @ bus 4

Condition:

$$\begin{cases} I^0 = I^+ = I^- \\ V^0 + V^+ + V^- = (3 \cdot Z_F) I^+ \end{cases}$$



$$I^0 = I^+ = I^- = \frac{V_{prefault}}{Z_{th}^0 + Z_{th}^+ + Z_{th}^- + (3 \cdot Z_F)}$$

@ I_F - segence

$$I_{F_4}^0 = \frac{1.05\angle 0^\circ}{j(0.0089 + 0.023 + 0.023)}$$

$$I_{F_4}^0 = I_{F_4}^+ = I_{F_4}^- = -j19.12 \text{ P.U.}$$

@ I_F Phase

$$[I_{F\text{-}phase}] = A \cdot [I_F \text{ segence}]$$

$$\begin{bmatrix} I_{F_4}^a \\ I_{F_4}^b \\ I_{F_4}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{F_4}^0 = -j19.12 \text{ P.U.} \\ I_{F_4}^+ = -j19.12 \text{ P.U.} \\ I_{F_4}^- = -j19.12 \text{ P.U.} \end{bmatrix}$$

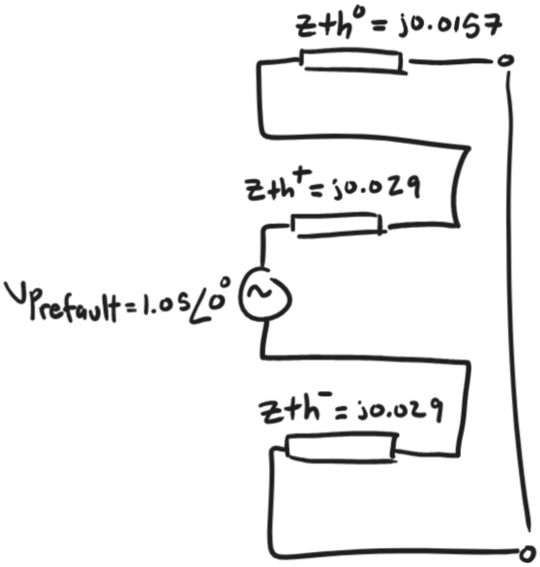
$\alpha = 1\angle 120^\circ$ $\quad$ $\alpha^2 = 1\angle -120^\circ = 1\angle 240^\circ$

$$\begin{bmatrix} I_{F_4}^a \\ I_{F_4}^b \\ I_{F_4}^c \end{bmatrix} = \begin{bmatrix} -j57.36 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \end{bmatrix}$$

@ Bolted Single line to ground Fault @ bus 5

Condition:

$$\begin{cases} I^0 = I^+ = I^- \\ V^0 + V^+ + V^- = (3 \cdot Z_F)\, I^+ \end{cases}$$



$$I^0 = I^+ = I^- = \frac{V_{Prefault}}{Z_{th}^0 + Z_{th}^+ + Z_{th}^- + (3 \cdot Z_F)}$$

@ I_F - segence

$$I_{F_5}^0 = \frac{1.05\angle 0^\circ}{j(0.0157 + 0.029 + 0.029)}$$

$$I_{F_5}^0 = I_{F_5}^+ = I_{F_5}^- = -j14.24 \text{ P.U.}$$

@ I_F Phase

$$[I_{F\text{-}Phase}] = A \cdot [I_F \text{ segence}]$$

$$\begin{bmatrix} I_{F_5}^a \\ I_{F_5}^b \\ I_{F_5}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \underset{1\angle 120^\circ}{\alpha} & \underset{1\angle -120^\circ = 1\angle 240^\circ}{\alpha^2} \end{bmatrix} \begin{bmatrix} I_{F_5}^0 = -j14.24 \text{ P.U.} \\ I_{F_5}^+ = -j14.24 \text{ P.U.} \\ I_{F_5}^- = -j14.24 \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} I_{F_5}^a \\ I_{F_5}^b \\ I_{F_5}^c \end{bmatrix} = \begin{bmatrix} -j42.72 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \end{bmatrix}$$

e) Use the sequence bus impedance matrices calculated in part (c) and the vector of sequence bus injected currents using the sequence fault currents calculated in part (d) to calculate the per-unit sequence bus voltages during each fault

$$\left(\begin{bmatrix} V_1(F) \\ V_2(F) \\ V_3(F) \\ V_4(F) \\ V_5(F) \end{bmatrix}^0, \begin{bmatrix} V_1(F) \\ V_2(F) \\ V_3(F) \\ V_4(F) \\ V_5(F) \end{bmatrix}^+, \begin{bmatrix} V_1(F) \\ V_2(F) \\ V_3(F) \\ V_4(F) \\ V_5(F) \end{bmatrix}^- \right).$$

@ Zero Seqence

@ $V_n^0(F)$, Fault @ bus 1

$$V_n^0(F) = (Zbus^0)(-IF_1^0)$$

$$\begin{bmatrix} V_1^0(F) \\ V_2^0(F) \\ V_3^0(F) \\ V_4^0(F) \\ V_5^0(F) \end{bmatrix} = j \begin{bmatrix} 0.0125 & 0 & 0 & 0 & 0 \\ 0 & 0.1089 & 0 & 0.0043 & 0.0112 \\ 0 & 0 & 0.0125 & 0 & 0 \\ 0 & 0.0043 & 0 & 0.0089 & 0.0021 \\ 0 & 0.0112 & 0 & 0.0021 & 0.0157 \end{bmatrix} \begin{bmatrix} -(-j15.78) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^0(F) \\ V_2^0(F) \\ V_3^0(F) \\ V_4^0(F) \\ V_5^0(F) \end{bmatrix} = \begin{bmatrix} -0.197 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \end{bmatrix}$$

@ $V_n^0(F)$, Fault @ bus 2

$$V_n^0(F) = (Z_{bus}^0)(-I_{F_2})$$

$$\begin{bmatrix} V_1^0(F) \\ V_2^0(F) \\ V_3^0(F) \\ V_4^0(F) \\ V_5^0(F) \end{bmatrix} = j\begin{bmatrix} 0.0125 & 0 & 0 & 0 & 0 \\ 0 & 0.1089 & 0 & 0.0043 & 0.0112 \\ 0 & 0 & 0.0125 & 0 & 0 \\ 0 & 0.0043 & 0 & 0.0089 & 0.0021 \\ 0 & 0.0112 & 0 & 0.0021 & 0.0157 \end{bmatrix}\begin{bmatrix} 0 \\ -(-j4.75) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^0(F) \\ V_2^0(F) \\ V_3^0(F) \\ V_4^0(F) \\ V_5^0(F) \end{bmatrix} = \begin{bmatrix} 0 \text{ P.U.} \\ -0.517 \text{ P.U.} \\ 0 \text{ P.U.} \\ -0.020 \text{ P.U.} \\ -0.053 \text{ P.U.} \end{bmatrix}$$

@ $V_n^0(F)$, Fault @ bus 3

$$V_n^0(F) = (Z_{bus}^0)(-I_{F_3})$$

$$\begin{bmatrix} V_1^0(F) \\ V_2^0(F) \\ V_3^0(F) \\ V_4^0(F) \\ V_5^0(F) \end{bmatrix} = j\begin{bmatrix} 0.0125 & 0 & 0 & 0 & 0 \\ 0 & 0.1089 & 0 & 0.0043 & 0.0112 \\ 0 & 0 & 0.0125 & 0 & 0 \\ 0 & 0.0043 & 0 & 0.0089 & 0.0021 \\ 0 & 0.0112 & 0 & 0.0021 & 0.0157 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ -(-j21.87) \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^0(F) \\ V_2^0(F) \\ V_3^0(F) \\ V_4^0(F) \\ V_5^0(F) \end{bmatrix} = \begin{bmatrix} 0 \text{ P.U.} \\ 0 \text{ P.U.} \\ -0.273 \text{ P.U.} \\ 0 \text{ P.U.} \\ 0 \text{ P.U.} \end{bmatrix}$$

@ $V_n^\circ(F)$, Fault @ bus 4

$$V_n^\circ(F) = (Z_{bus}^\circ)(-I_{F_4})$$

$$\begin{bmatrix} V_1^\circ(F) \\ V_2^\circ(F) \\ V_3^\circ(F) \\ V_4^\circ(F) \\ V_5^\circ(F) \end{bmatrix} = j\begin{bmatrix} 0.0125 & 0 & 0 & 0 & 0 \\ 0 & 0.1089 & 0 & 0.0043 & 0.0112 \\ 0 & 0 & 0.0125 & 0 & 0 \\ 0 & 0.0043 & 0 & 0.0089 & 0.0021 \\ 0 & 0.0112 & 0 & 0.0021 & 0.0157 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ 0 \\ -(-j19.12) \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^\circ(F) \\ V_2^\circ(F) \\ V_3^\circ(F) \\ V_4^\circ(F) \\ V_5^\circ(F) \end{bmatrix} = \begin{bmatrix} 0 \text{ P.U.} \\ -0.082 \text{ P.U.} \\ 0 \text{ P.U.} \\ -0.170 \text{ P.U.} \\ -0.040 \text{ P.U.} \end{bmatrix}$$

@ $V_n^\circ(F)$, Fault @ bus 5

$$V_n^\circ(F) = (Z_{bus}^\circ)(-I_{F_5})$$

$$\begin{bmatrix} V_1^\circ(F) \\ V_2^\circ(F) \\ V_3^\circ(F) \\ V_4^\circ(F) \\ V_5^\circ(F) \end{bmatrix} = j\begin{bmatrix} 0.0125 & 0 & 0 & 0 & 0 \\ 0 & 0.1089 & 0 & 0.0043 & 0.0112 \\ 0 & 0 & 0.0125 & 0 & 0 \\ 0 & 0.0043 & 0 & 0.0089 & 0.0021 \\ 0 & 0.0112 & 0 & 0.0021 & 0.0157 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -(-j14.24) \end{bmatrix}$$

$$\begin{bmatrix} V_1^\circ(F) \\ V_2^\circ(F) \\ V_3^\circ(F) \\ V_4^\circ(F) \\ V_5^\circ(F) \end{bmatrix} = \begin{bmatrix} 0 \text{ P.U.} \\ -0.159 \text{ P.U.} \\ 0 \text{ P.U.} \\ -0.029 \text{ P.U.} \\ -0.224 \text{ P.U.} \end{bmatrix}$$

@ Positive Seqence

@ $V_n^+(F)$, Fault @ bus 1

$$V_n^+(F) = V_{prefault} + Zbus^+ (I_{F_1}^+)$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \end{bmatrix} + j \begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix} \begin{bmatrix} -(-j15.78) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 0.623 \text{ P.U.} \\ 0.781 \text{ P.U.} \\ 0.923 \text{ P.U.} \\ 0.860 \text{ P.U.} \\ 0.734 \text{ P.U.} \end{bmatrix}$$

@ $V_n^+(F)$, Fault @ bus 2

$$V_n^+(F) = V_{prefault} + Zbus^+ (I_{F_2}^+)$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \end{bmatrix} + j \begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix} \begin{bmatrix} 0 \\ -(-j4.75) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 0.969 \text{ P.U.} \\ 0.784 \text{ P.U.} \\ 0.988 \text{ P.U.} \\ 0.959 \text{ P.U.} \\ 0.931 \text{ P.U.} \end{bmatrix}$$

@ $V_n^+(F)$, Fault @ bus 3

$$V_n^+(F) = V_{prefault} + Zbus^+ (I_{F_3}^+)$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \end{bmatrix} + j \begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -(-j21.87) \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 0.875 \text{ P.U.} \\ 0.765 \text{ P.U.} \\ 0.656 \text{ P.U.} \\ 0.700 \text{ P.U.} \\ 0.787 \text{ P.U.} \end{bmatrix}$$

@ $V_n^+(F)$, Fault @ bus 4

$$V_n^+(F) = V_{prefault} + Zbus^+ (I_{F_4}^+)$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \end{bmatrix} + j \begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ -(-j19.12) \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 0.820 \text{ P.U.} \\ 0.686 \text{ P.U.} \\ 0.744 \text{ P.U.} \\ 0.610 \text{ P.U.} \\ 0.724 \text{ P.U.} \end{bmatrix}$$

@ $V_n^+(F)$, Fault @ bus 5

$$V_n^+(F) = V_{Prefault} + Zbus^+ (I_{F_5}^+)$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \\ 1.05 \end{bmatrix} + j \begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -(-j14.24) \end{bmatrix}$$

$$\begin{bmatrix} V_1^+(F) \\ V_2^+(F) \\ V_3^+(F) \\ V_4^+(F) \\ V_5^+(F) \end{bmatrix} = \begin{bmatrix} 0.765 \\ 0.694 \\ 0.879 \\ 0.807 \\ 0.637 \end{bmatrix}$$

@ Negative Seqence

@ $V_n^-(F)$, Fault @ bus 1

$$V_n^-(F) = Zbus^- (I_{F_1}^-)$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = j \begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix} \begin{bmatrix} -(-j15.78) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = \begin{bmatrix} -0.426 \\ -0.268 \\ -0.126 \\ -0.189 \\ -0.315 \end{bmatrix}$$

@ $V_n^-(F)$, Fault @ bus 2

$$V_n^-(F) = Zbus^-(I_{F_2}^-)$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = j\begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix}\begin{bmatrix} 0 \\ -(-j4.75) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = \begin{bmatrix} -0.080 \\ -0.266 \\ -0.061 \\ -0.09 \\ -0.118 \end{bmatrix}$$

@ $V_n^-(F)$, Fault @ bus 3

$$V_n^-(F) = Zbus^-(I_{F_3}^-)$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = j\begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ -(-j21.87) \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = \begin{bmatrix} -0.174 \\ -0.284 \\ -0.393 \\ -0.349 \\ -0.262 \end{bmatrix}$$

@ $V_n^-(F)$, Fault @ bus 4

$$V_n^-(F) = Z_{bus}^-(I_{F_4}^-)$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = j\begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ 0 \\ -(-j19.12) \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = \begin{bmatrix} -0.229 \\ -0.363 \\ -0.305 \\ -0.439 \\ -0.325 \end{bmatrix}$$

@ $V_n^-(F)$, Fault @ bus 5

$$V_n^-(F) = Z_{bus}^-(I_{F_5}^-)$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = j\begin{bmatrix} 0.027 & 0.017 & 0.008 & 0.012 & 0.020 \\ 0.017 & 0.056 & 0.013 & 0.019 & 0.025 \\ 0.008 & 0.013 & 0.018 & 0.016 & 0.012 \\ 0.012 & 0.019 & 0.016 & 0.023 & 0.017 \\ 0.020 & 0.025 & 0.012 & 0.017 & 0.029 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -(-j14.24) \end{bmatrix}$$

$$\begin{bmatrix} V_1^-(F) \\ V_2^-(F) \\ V_3^-(F) \\ V_4^-(F) \\ V_5^-(F) \end{bmatrix} = \begin{bmatrix} -0.284 \\ -0.356 \\ -0.170 \\ -0.242 \\ -0.412 \end{bmatrix}$$

$V_n(F)$ @ bus 1

$$\begin{bmatrix} V_1^0(F) = -0.197 \text{ P.U.} \\ V_2^0(F) = 0 \text{ P.U.} \\ V_3^0(F) = 0 \text{ P.U.} \\ V_4^0(F) = 0 \text{ P.U.} \\ V_5^0(F) = 0 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^+(F) = 0.623 \text{ P.U.} \\ V_2^+(F) = 0.781 \text{ P.U.} \\ V_3^+(F) = 0.923 \text{ P.U.} \\ V_4^+(F) = 0.860 \text{ P.U.} \\ V_5^+(F) = 0.734 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^-(F) = -0.426 \text{ P.U.} \\ V_2^-(F) = -0.268 \text{ P.U.} \\ V_3^-(F) = -0.126 \text{ P.U.} \\ V_4^-(F) = -0.189 \text{ P.U.} \\ V_5^-(F) = -0.315 \text{ P.U.} \end{bmatrix}$$

$V_n(F)$ @ bus 2

$$\begin{bmatrix} V_1^0(F) = 0 \text{ P.U.} \\ V_2^0(F) = -0.517 \text{ P.U.} \\ V_3^0(F) = 0 \text{ P.U.} \\ V_4^0(F) = -0.020 \text{ P.U.} \\ V_5^0(F) = -0.053 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^+(F) = 0.969 \text{ P.U.} \\ V_2^+(F) = 0.784 \text{ P.U.} \\ V_3^+(F) = 0.988 \text{ P.U.} \\ V_4^+(F) = 0.959 \text{ P.U.} \\ V_5^+(F) = 0.931 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^-(F) = -0.080 \text{ P.U.} \\ V_2^-(F) = -0.266 \text{ P.U.} \\ V_3^-(F) = -0.061 \text{ P.U.} \\ V_4^-(F) = -0.09 \text{ P.U.} \\ V_5^-(F) = -0.118 \text{ P.U.} \end{bmatrix}$$

$V_n(F)$ @ bus 3

$$\begin{bmatrix} V_1^0(F) = 0 \text{ P.U.} \\ V_2^0(F) = 0 \text{ P.U.} \\ V_3^0(F) = -0.273 \text{ P.U.} \\ V_4^0(F) = 0 \text{ P.U.} \\ V_5^0(F) = 0 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^+(F) = 0.875 \text{ P.U.} \\ V_2^+(F) = 0.765 \text{ P.U.} \\ V_3^+(F) = 0.656 \text{ P.U.} \\ V_4^+(F) = 0.700 \text{ P.U.} \\ V_5^+(F) = 0.787 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^-(F) = -0.174 \text{ P.U.} \\ V_2^-(F) = -0.284 \text{ P.U.} \\ V_3^-(F) = -0.393 \text{ P.U.} \\ V_4^-(F) = -0.349 \text{ P.U.} \\ V_5^-(F) = -0.262 \text{ P.U.} \end{bmatrix}$$

$V_n(F)$ @ bus 4

$$\begin{bmatrix} V_1^0(F) = 0 \text{ P.U.} \\ V_2^0(F) = -0.082 \text{ P.U.} \\ V_3^0(F) = 0 \text{ P.U. P.U.} \\ V_4^0(F) = -0.170 \text{ P.U.} \\ V_5^0(F) = -0.040 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^+(F) = 0.820 \text{ P.U.} \\ V_2^+(F) = 0.686 \text{ P.U.} \\ V_3^+(F) = 0.744 \text{ P.U.} \\ V_4^+(F) = 0.610 \text{ P.U.} \\ V_5^+(F) = 0.724 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^-(F) = -0.229 \text{ P.U.} \\ V_2^-(F) = -0.363 \text{ P.U.} \\ V_3^-(F) = -0.305 \text{ P.U.} \\ V_4^-(F) = -0.439 \text{ P.U.} \\ V_5^-(F) = -0.325 \text{ P.U.} \end{bmatrix}$$

$V_n(F)$ @ bus 5

$$\begin{bmatrix} V_1^0(F) = 0 \text{ P.U.} \\ V_2^0(F) = -0.159 \\ V_3^0(F) = 0 \text{ P.U.} \\ V_4^0(F) = -0.029 \text{ P.U.} \\ V_5^0(F) = -0.224 \text{ P.U.} \end{bmatrix}, \begin{bmatrix} V_1^+(F) = 0.765 \\ V_2^+(F) = 0.694 \\ V_3^+(F) = 0.879 \\ V_4^+(F) = 0.807 \\ V_5^+(F) = 0.637 \end{bmatrix}, \begin{bmatrix} V_1^-(F) = -0.284 \text{ P.U.} \\ V_2^-(F) = -0.356 \text{ P.U.} \\ V_3^-(F) = -0.170 \text{ P.U.} \\ V_4^-(F) = -0.242 \text{ P.U.} \\ V_5^-(F) = -0.412 \text{ P.U.} \end{bmatrix}$$

Use the calculated sequence components of the voltages for each bus and the transformation matrix to calculate the phase components of the bus voltages during each fault (20 points).

$$\left(\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix}, \begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix}, \begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix}, \begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix}, \begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix}\right).$$

$V_n(F)$ Bus Voltage @ Fault 1

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_1^0(F) = -0.197 \\ V_1^+(F) = 0.623 \\ V_1^-(F) = -0.426 \end{bmatrix}$$

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 0 \text{ P.U.} \\ 0.955\angle -108.0^\circ \text{ P.U.} \\ 0.955\angle 108.0^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_2^0(F) = 0 \\ V_2^+(F) = 0.781 \\ V_2^-(F) = -0.268 \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 0.513\angle 0^\circ \text{ P.U.} \\ 0.943\angle -105.76^\circ \text{ P.U.} \\ 0.943\angle 105.76^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_3^0(F) = 0 \\ V_3^+(F) = 0.923 \\ V_3^-(F) = -0.126 \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 0.797\angle 0^\circ \text{ P.U.} \\ 0.99\angle -113.68^\circ \text{ P.U.} \\ 0.99\angle 113.68^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_4^0(F) = 0 \\ V_4^+(F) = 0.860 \\ V_4^-(F) = -0.189 \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 0.671\angle 0^\circ \text{ P.U.} \\ 0.968\angle -110.26^\circ \text{ P.U.} \\ 0.968\angle 110.26^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_5^0(F) = 0 \\ V_5^+(F) = 0.734 \\ V_5^-(F) = -0.315 \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 0.419\angle 0^\circ \text{ P.U.} \\ 0.932\angle -102.98^\circ \text{ P.U.} \\ 0.932\angle 102.98^\circ \text{ P.U.} \end{bmatrix}$$

$V_n(F)$ Bus voltage @ Fault 2

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_1^0(F) = 0 \\ V_1^+(F) = 0.969 \\ V_1^-(F) = -0.08 \end{bmatrix}$$

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 0.889\angle 0^\circ \text{ P.U.} \\ 1.01 \angle -116.07^\circ \text{ P.U.} \\ 1.01 \angle 116.07^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_2^0(F) = -0.517 \\ V_2^+(F) = 0.784 \\ V_2^-(F) = -0.266 \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 0.001 \angle 0^\circ \text{ P.U.} \\ 1.19 \angle -130.47^\circ \text{ P.U.} \\ 1.19 \angle 130.47^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_3^0(F) = 0 \\ V_3^+(F) = 0.988 \\ V_3^-(F) = -0.061 \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 0.927\angle 0^\circ \text{ P.U.} \\ 1.01 \angle -117.03^\circ \text{ P.U.} \\ 1.01 \angle 117.03^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_4^0(F) = -0.02 \\ V_4^+(F) = 0.959 \\ V_4^-(F) = -0.09 \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 0.849\angle 0^\circ \text{ P.U.} \\ 1.01 \angle -116.57^\circ \text{ P.U.} \\ 1.01 \angle 116.57^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_5^0(F) = -0.053 \\ V_5^+(F) = 0.931 \\ V_5^-(F) = -0.118 \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 0.76\angle 0^\circ \text{ P.U.} \\ 1.01 \angle -116.83^\circ \text{ P.U.} \\ 1.01 \angle 116.83^\circ \text{ P.U.} \end{bmatrix}$$

$V_n(F)$ Bus Voltage @ Fault 3

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_1^0(F) = 0 \\ V_1^+(F) = 0.879 \\ V_1^-(F) = -0.179 \end{bmatrix}$$

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 0.701\angle 0^\circ \text{ P.U.} \\ 0.973\angle -111^\circ \text{ P.U.} \\ 0.973\angle 111^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_3^0(F) = -0.273 \\ V_3^+(F) = 0.656 \\ V_3^-(F) = -0.393 \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 0.01\angle 180^\circ \text{ P.U.} \\ 0.994\angle -114^\circ \text{ P.U.} \\ 0.994\angle 114^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_2^0(F) = 0 \\ V_2^+(F) = 0.765 \\ V_2^-(F) = -0.284 \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 0.481\angle 0^\circ \text{ P.U.} \\ 0.939\angle -104.82^\circ \text{ P.U.} \\ 0.939\angle 104.82^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_4^0(F) = 0 \\ V_4^+(F) = 0.7 \\ V_4^-(F) = -0.349 \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 0.351\angle 0^\circ \text{ P.U.} \\ 0.925\angle -100.9^\circ \text{ P.U.} \\ 0.925\angle 100.9^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_5^0(F) = 0 \\ V_5^+(F) = 0.787 \\ V_5^-(F) = -0.262 \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 0.525\angle 0^\circ \text{ P.U.} \\ 0.945\angle -106.11^\circ \text{ P.U.} \\ 0.945\angle 106.11^\circ \text{ P.U.} \end{bmatrix}$$

$V_n(F)$ Bus Voltage @ Fault 4

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_1^0(F) = 0 \\ V_1^+(F) = 0.820 \\ V_1^-(F) = -0.229 \end{bmatrix}$$

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 0.591\angle 0^\circ \text{ P.U.} \\ 0.955\angle -108^\circ \text{ P.U.} \\ 0.955\angle 108^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_2^0(F) = -0.082 \\ V_2^+(F) = 0.686 \\ V_2^-(F) = -0.363 \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 0.241\angle 0^\circ \text{ P.U.} \\ 0.940\angle -105^\circ \text{ P.U.} \\ 0.940\angle 105.0^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_3^0(F) = 0 \\ V_3^+(F) = 0.744 \\ V_3^-(F) = -0.305 \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 0.438\angle 0^\circ \text{ P.U.} \\ 0.935\angle -103.54^\circ \text{ P.U.} \\ 0.935\angle 103.54^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_4^0(F) = -0.170 \\ V_4^+(F) = 0.610 \\ V_4^-(F) = -0.439 \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 0.001\angle 0^\circ \text{ P.U.} \\ 0.943\angle -105.7^\circ \text{ P.U.} \\ 0.943\angle 105.7^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_5^0(F) = -0.04 \\ V_5^+(F) = 0.724 \\ V_5^-(F) = -0.325 \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 0.359\angle 0^\circ \text{ P.U.} \\ 0.939\angle -104.76^\circ \text{ P.U.} \\ 0.939\angle 104.76^\circ \text{ P.U.} \end{bmatrix}$$

$V_n(F)$ Bus Voltage @ Fault 5

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_1^0(F) = 0 \\ V_1^+(F) = 0.765 \\ V_1^-(F) = -0.284 \end{bmatrix}$$

$$\begin{bmatrix} V_1^a(F) \\ V_1^b(F) \\ V_1^c(F) \end{bmatrix} = \begin{bmatrix} 0.481\angle 0^\circ \text{ P.U.} \\ 0.939\angle -104.82^\circ \text{ P.U.} \\ 0.939\angle 104.82^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_3^0(F) = 0 \\ V_3^+(F) = 0.879 \\ V_3^-(F) = -0.170 \end{bmatrix}$$

$$\begin{bmatrix} V_3^a(F) \\ V_3^b(F) \\ V_3^c(F) \end{bmatrix} = \begin{bmatrix} 0.709\angle 0^\circ \text{ P.U.} \\ 0.975\angle -111^\circ \text{ P.U.} \\ 0.975\angle 111^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_2^0(F) = -0.159 \\ V_2^+(F) = 0.694 \\ V_2^-(F) = -0.356 \end{bmatrix}$$

$$\begin{bmatrix} V_2^a(F) \\ V_2^b(F) \\ V_2^c(F) \end{bmatrix} = \begin{bmatrix} 0.179\angle 0^\circ \text{ P.U.} \\ 0.966\angle -109.83^\circ \text{ P.U.} \\ 0.966\angle 109.83^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_4^0(F) = -0.029 \\ V_4^+(F) = 0.807 \\ V_4^-(F) = -0.242 \end{bmatrix}$$

$$\begin{bmatrix} V_4^a(F) \\ V_4^b(F) \\ V_4^c(F) \end{bmatrix} = \begin{bmatrix} 0.536\angle 0^\circ \text{ P.U.} \\ 0.96\angle -108.9^\circ \text{ P.U.} \\ 0.96\angle 108.9^\circ \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_5^0(F) = -0.244 \\ V_5^+(F) = 0.637 \\ V_5^-(F) = -0.412 \end{bmatrix}$$

$$\begin{bmatrix} V_5^a(F) \\ V_5^b(F) \\ V_5^c(F) \end{bmatrix} = \begin{bmatrix} -0.019\angle 0^\circ \text{ P.U.} \\ 0.975\angle -111.42^\circ \text{ P.U.} \\ 0.975\angle 111.42^\circ \text{ P.U.} \end{bmatrix}$$

f) Use the sequence bus voltages calculated in part (e) and the sequence reactance diagrams calculated in part (a) to calculate the sequence components of the contributions to the fault current for each fault as follows:

f1) Sequence components of the fault current contributions from Generator 1 and Transformer 1 ($IG1\ 0\ (F)$,$IG1 + (F)$,$IG1 - (F)$, $IT1\ 0\ (F)$,$IT1 + (F)$,$IT1 - (F)$) for the fault at bus 1.

@ I_{G1} Sepence

$$I_{g1}^{0} = \frac{GND - V_1^0(F)}{X_{g1}^{0}} = \frac{0-(-0.197)}{j0.0125} = -j15.76\ P.U.$$

$$I_{g1}^{+} = \frac{V_{Prefault} - V_1^{+}(F)}{X_{g1}^{+}} = \frac{1.05-(0.623)}{j0.045} = -j9.48\ P.U.$$

$$I_{g1}^{-} = \frac{(GND) - V_1^{-}(F)}{X_{g1}^{-} =} = \frac{0-(-0.426)}{j0.045} = -j9.46\ P.U.$$

@ I_{g1} Phase

$$\begin{bmatrix} I_{g1}^{a} \\ I_{g1}^{b} \\ I_{g1}^{c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{g1}^{0} = -j15.76 \\ I_{g1}^{+} = -j9.48 \\ I_{g1}^{-} = -j9.46 \end{bmatrix}$$

$$\begin{bmatrix} I_{g1}^{a} \\ I_{g1}^{b} \\ I_{g1}^{c} \end{bmatrix} = \begin{bmatrix} 34.7\angle -90\ P.U. \\ 6.29\angle -90.15\ P.U. \\ 6.29\angle -89.84\ P.U. \end{bmatrix}$$

// redo T1

@ I_{T_1} Seqence

$$I_{T_1}^0 = \frac{V_s^0(F) - GND}{X_{T_1}^0} = \frac{0-0}{j0.02} = 0 \text{ P.U.}$$

$$X_{T_1}^+ = \frac{V_s^+(F) - V_1^+(F)}{X_{T_1}^+} = \frac{0.734 - 0.623}{j0.02} = -j5.55 \text{ P.U.}$$

$$X_{T_1}^- = \frac{V_s^-(F) - V_1^-(F)}{X_{T_1}^-} = \frac{(-0.315)-(-0.426)}{j0.02} = -j5.55 \text{ P.U.}$$

@ I_{T_1} Phase

$$\begin{bmatrix} I_{T_1}^a \\ I_{T_1}^b \\ I_{T_1}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{T_1}^0 = 0 \\ I_{T_1}^+ = -j5.55 \\ I_{T_1}^- = -j5.55 \end{bmatrix}$$

$$\begin{bmatrix} I_{T_1}^0 \\ I_{T_1}^+ \\ I_{T_1}^- \end{bmatrix} = \begin{bmatrix} -j11.1 \text{ P.U.} \\ j5.55 \text{ P.U.} \\ j5.55 \text{ P.U.} \end{bmatrix}$$

f2) Sequence components of the fault current contributions from Line 1 and Line 2 ($IL1\ 0$ (F),$IL1 +(F)$,$IL1 -(F)$, $IL2\ 0\ (F)$,$IL2 +(F)$,$IL2 -(F)$) for the fault at bus 2.

@ I_{Line_1} Seqence

$$I_{Line_1}^{0} = \frac{V_2^0(F) - V_4^0(F)}{Z_{Line_1}^{0}} = \frac{(-0.020)-(-0.517)}{j0.3} = -j1.65 \text{ P.U.}$$

$$I_{Line_1}^{+} = \frac{V_2^+(F) - V_4^+(F)}{Z_{Line_1}^{+}} = \frac{0.959 - 0.784}{j0.1} = -j1.75 \text{ P.U.}$$

$$I_{Line_1}^{-} = \frac{V_2^-(F) - V_4^-(F)}{Z_{Line_1}^{-}} = \frac{(-0.09)-(-0.266)}{j0.1} = -j1.76 \text{ P.U.}$$

@ I_{Line_1} Phase

$$\begin{bmatrix} I_{Line_1}^{a} \\ I_{Line_1}^{b} \\ I_{Line_1}^{c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{Line_1}^{0} = -j1.65 \\ I_{Line_1}^{+} = -j1.75 \\ I_{Line_1}^{-} = -j1.76 \end{bmatrix}$$

$$\begin{bmatrix} I_{Line_1}^{a} \\ I_{Line_1}^{b} \\ I_{Line_1}^{c} \end{bmatrix} = \begin{bmatrix} 5.16\angle 90^\circ \text{ P.U.} \\ 0.105\angle -94.71^\circ \text{ P.U.} \\ 0.105\angle -85.28^\circ \text{ P.U.} \end{bmatrix}$$

// **redo Line 2**

@ I_{Line_2} Seqence

$$I_{Line_2}^{0} = \frac{V_5^0(F) - V_2^0(F)}{Z_{Line_2}^0} = \frac{(-0.053)-(-0.517)}{j0.15} = -j3.09 \text{ P.U.}$$

$$I_{Line_2}^{+} = \frac{V_5^+(F) - V_2^+(F)}{Z_{Line_2}^+} = \frac{0.931 - 0.784}{j0.05} = -j2.94 \text{ P.U.}$$

$$I_{Line_2}^{-} = \frac{V_5^-(F) - V_2^-(F)}{Z_{Line_2}^-} = \frac{(-0.118)-(-0.266)}{j0.05} = -j2.96 \text{ P.U.}$$

@ I_{Line_2} Phase

$$\begin{bmatrix} I_{Line_2}^{a} \\ I_{Line_2}^{b} \\ I_{Line_2}^{c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{Line_2}^{0} = -j3.09 \text{ P.U.} \\ I_{Line_2}^{+} = -j2.94 \text{ P.U.} \\ I_{Line_2}^{-} = -j2.96 \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} I_{Line_2}^{a} \\ I_{Line_2}^{b} \\ I_{Line_2}^{c} \end{bmatrix} = \begin{bmatrix} 8.99\angle -90^\circ \text{ P.U.} \\ 0.14\angle -82.94^\circ \text{ P.U.} \\ 0.14\angle -97.05^\circ \text{ P.U.} \end{bmatrix}$$

f3) Sequence components of the fault current contributions from Generator 2 and Transformer 2 ($I_{G2}^{0}(F)$, $I_{G2}^{+}(F)$, $I_{G2}^{-}(F)$, $I_{T2}^{0}(F)$, $I_{T2}^{+}(F)$, $I_{T2}^{-}(F)$) for the fault at bus 3.

@ I_{g2} Seqence

$$I_{g2}^{0} = \frac{GND - V_3^{0}(F)}{X_{g2}^{0} + 3Z_n} = \frac{0-(-0.273)}{j0.005+j0.0075} = -j21.84 \text{ P.U.}$$

$$I_{g2}^{+} \quad \frac{V_{prefault} - V_3^{+}(F)}{X_{g2}^{+}} = \frac{1.05-(0.656)}{j0.0225} = -j17.51 \text{ P.U.}$$

$$I_{g2}^{-} = \frac{GND - V_3^{-}(F)}{X_{g2}^{-}} = \frac{0-(-0.393)}{j0.0225} = -j17.46 \text{ P.U.}$$

@ I_{g2} Phase

$$\begin{bmatrix} I_{g2}^{a} \\ I_{g2}^{b} \\ I_{g2}^{c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{g2}^{0} = -j21.84 \\ I_{g2}^{+} = -j17.51 \\ I_{g2}^{-} = -j17.46 \end{bmatrix}$$

$$\begin{bmatrix} I_{g2}^{a} \\ I_{g2}^{b} \\ I_{g2}^{c} \end{bmatrix} = \begin{bmatrix} 56.81\angle -90^\circ \text{ P.U.} \\ 4.35\angle -90^\circ \text{ P.U.} \\ 4.35\angle -89^\circ \text{ P.U.} \end{bmatrix}$$

@ I_{T_2} seqence

$$I_{T_2}^{0} = \frac{V_4^0(F) - V_3^0(F)}{X_{T_1}^0} = \frac{0-(-0.273)}{0} = 0 \text{ P.U.}$$

$$I_{T_2}^{+} = \frac{V_4^+(F) - V_3^+(F)}{X_{T_1}^+} = \frac{0.7-(0.656)}{j0.01} = -j4.4 \text{ P.U.}$$

$$I_{T_2}^{-} = \frac{V_4^-(F) - V_3^-(F)}{X_{T_1}^-} = \frac{(-0.349)-(-0.393)}{j0.01} = -j4.4 \text{ P.U.}$$

@ I_{T_2} Phase

$$\begin{bmatrix} I_{T_2}^a \\ I_{T_2}^b \\ I_{T_2}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{T_2}^0 = 0 \\ I_{T_2}^+ = -j4.4 \\ I_{T_2}^- = -j4.4 \end{bmatrix}$$

$$\begin{bmatrix} I_{T_2}^a \\ I_{T_2}^b \\ I_{T_2}^c \end{bmatrix} = \begin{bmatrix} -j8.8 \text{ P.U.} \\ j4.4 \text{ P.U.} \\ j4.4 \text{ P.U.} \end{bmatrix}$$

f4) Sequence components of the fault current contributions from Line 1, Line 3, and Transformer 2 ($I_{L1}^0(F)$, $I_{L1}^+(F)$, $I_{L1}^-(F)$, $I_{L3}^0(F)$, $I_{L3}^+(F)$, $I_{L3}^-(F)$, $I_{T2}^0(F)$, $I_{T2}^+(F)$, $I_{T2}^-(F)$) for the fault at bus 4.

@ I_{Line_1} Seqence

$$I_{Line_1}^0 = \frac{V_2^0(F) - V_4^0(F)}{Z_{Line_1}^0} = \frac{(-0.082)-(-0.170)}{j0.3} = -j0.29 \text{ P.U.}$$

$$I_{Line_1}^+ = \frac{V_2^+(F) - V_4^+(F)}{Z_{Line_1}^+} = \frac{0.686 - 0.610}{j0.1} = -j0.76 \text{ P.U.}$$

$$I_{Line_1}^- = \frac{V_2^-(F) - V_4^-(F)}{Z_{Line_1}^-} = \frac{(-0.363)-(-0.439)}{j0.1} = -j76 \text{ P.U.}$$

@ I_{Line_1} Phase

$$\begin{bmatrix} I_{Line_1}^a \\ I_{Line_1}^b \\ I_{Line_1}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{Line_2}^0 = -j0.29 \\ I_{Line_2}^+ = -j0.76 \\ I_{Line_2}^- = -j0.76 \end{bmatrix}$$

$$\begin{bmatrix} I_{Line_1}^a \\ I_{Line_1}^b \\ I_{Line_1}^c \end{bmatrix} = \begin{bmatrix} 1.81\angle -90^\circ \text{ P.U.} \\ 0.47\angle 90^\circ \text{ P.U.} \\ 0.47\angle 90^\circ \text{ P.U.} \end{bmatrix}$$

@ I_{Line_3} Seqence

$$I_{Line_3}^{0} = \frac{V_5^0(F) - V_4^0(F)}{Z_{Line_3}^0} = \frac{(-0.04) - (-0.170)}{j0.075} = -j1.73 \text{ P.U.}$$

$$I_{Line_3}^{+} = \frac{V_5^+(F)_5 - V_4^+(F)}{Z_{Line_3}^+} = \frac{0.724 - 0.610}{j0.025} = -j4.56 \text{ P.U.}$$

$$I_{Line_3}^{-} = \frac{V_5^-(F) - V_4^-(F)}{Z_{Line_3}^-} = \frac{(-0.325) - (-0.439)}{j0.025} = -j4.56 \text{ P.U.}$$

@ I_{Line_3} Phase

$$\begin{bmatrix} I_{Line_3}^{a} \\ I_{Line_3}^{b} \\ I_{Line_3}^{c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{Line_3}^{0} = -j1.73 \text{ P.U.} \\ I_{Line_3}^{+} = -j4.56 \text{ P.U.} \\ I_{Line_3}^{-} = -j4.56 \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} I_{Line_3}^{a} \\ I_{Line_3}^{b} \\ I_{Line_3}^{c} \end{bmatrix} = \begin{bmatrix} 10.85\angle -90^\circ \text{ P.U.} \\ 2.83\angle 90^\circ \text{ P.U.} \\ 2.83\angle 90^\circ \text{ P.U.} \end{bmatrix}$$

@ I_{T_2} seqence

$$I_{T_2}^{0} = \frac{V_4^{0}(F) - V_3^{0}(F)}{X_{T_2}^{0}} = \frac{0-(-0.170)}{j0.01} = -j17 \text{ P.U.}$$

$$I_{T_2}^{+} = \frac{V_4^{+}(F) - V_3^{+}(F)}{X_{T_2}^{+}} = \frac{(0.744)-(0.610)}{j0.01} = -j13.4 \text{ P.U.}$$

$$I_{T_2}^{-} = \frac{V_4^{-}(F) - V_3^{-}(F)}{X_{T_2}^{-}} = \frac{(-0.305)-(-0.439)}{j0.01} = -j13.4 \text{ P.U.}$$

@ I_{T_2} Phase

$$\begin{bmatrix} I_{T_2}^{a} \\ I_{T_2}^{b} \\ I_{T_2}^{c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{T_2}^{0} = -j17 \\ I_{T_2}^{+} = -j13.4 \\ I_{T_2}^{-} = -j13.4 \end{bmatrix}$$

$$\begin{bmatrix} I_{T_2}^{a} \\ I_{T_2}^{b} \\ I_{T_2}^{c} \end{bmatrix} = \begin{bmatrix} -j43.8 \text{ P.U.} \\ -j3.6 \text{ P.U.} \\ -j3.6 \text{ P.U.} \end{bmatrix}$$

f5) Sequence components of the fault current contributions from Line 2, Line 3, and Transformer 1 ($IL2\ 0\ (F)$,$IL2+(F)$,$IL2-(F)$, $IL3\ 0\ (F)$,$IL3+(F)$,$IL3-(F)$,$IT1\ 0\ (F)$,$IT1+(F)$,$IT1-(F)$) for the fault at bus 5. Use the calculated sequence components and the transformation matrix to calculate the phase components of the fault current contributions in parts (f1)-(f5). (20 Points)

@ I_{Line_2} Seqence

$$I_{Line_2}^{0} = \frac{V_2^0(F) - V_5^0(F)}{Z_{Line_2}^0} = \frac{(-0.159) - (-0.224)}{j0.15} = -j0.43 \text{ P.U.}$$

$$I_{Line_2}^{+} = \frac{V_2^+(F) - V_5^+(F)}{Z_{Line_2}^+} = \frac{0.694 - 0.637}{j0.05} = -j1.14 \text{ P.U.}$$

$$I_{Line_2}^{-} = \frac{V_2^-(F) - V_5^-(F)}{Z_{Line_2}^-} = \frac{(-0.356) - (-0.412)}{j0.05} = -j1.12 \text{ P.U.}$$

@ I_{Line_2} Phase

$$\begin{bmatrix} I_{Line_2}^a \\ I_{Line_2}^b \\ I_{Line_2}^c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{Line_2}^0 = -j0.43 \text{ P.U.} \\ I_{Line_2}^+ = -j1.14 \text{ P.U.} \\ I_{Line_2}^- = -j1.12 \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} I_{Line_2}^a \\ I_{Line_2}^b \\ I_{Line_2}^c \end{bmatrix} = \begin{bmatrix} 2.69\angle -90^\circ \text{ P.U.} \\ 0.7\angle 91.41^\circ \text{ P.U.} \\ 0.7\angle 88.58^\circ \text{ P.U.} \end{bmatrix}$$

@ I_{Line_3} Seqence

$$I_{Line_3}^{0} = \frac{V_5^{0}(F) - V_4^{0}(F)}{Z_{Line_3}^{0}} = \frac{(-0.029) - (-0.224)}{j0.075} = -j2.6 \text{ P.U.}$$

$$I_{Line_3}^{+} = \frac{V_5^{+}(F)_5 - V_4^{+}(F)}{Z_{Line_3}^{+}} = \frac{0.807 - 0.637}{j0.025} = -j6.8 \text{ P.U.}$$

$$I_{Line_3}^{-} = \frac{V_5^{-}(F) - V_4^{-}(F)}{Z_{Line_3}^{-}} = \frac{(-0.242) - (-0.412)}{j0.025} = -j6.8 \text{ P.U.}$$

@ I_{Line_3} Phase

$$\begin{bmatrix} I_{Line_3}^{a} \\ I_{Line_3}^{b} \\ I_{Line_3}^{c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{Line_3}^{0} = -j2.6 \text{ P.U.} \\ I_{Line_3}^{+} = -j6.8 \text{ P.U.} \\ I_{Line_3}^{-} = -j6.8 \text{ P.U.} \end{bmatrix}$$

$$\begin{bmatrix} I_{Line_3}^{a} \\ I_{Line_3}^{b} \\ I_{Line_3}^{c} \end{bmatrix} = \begin{bmatrix} 16.2 \angle -90^\circ \text{ P.U.} \\ 4.2 \angle 90^\circ \text{ P.U.} \\ 4.2 \angle 90^\circ \text{ P.U.} \end{bmatrix}$$

@ I_{T_1} Seqence

$$I_{T_1}^{0} = \frac{GND - V_S^{0}(F)}{X_{T_1}^{0}} = \frac{0-(-0.244)}{j0.02} = -j12.2 \text{ P.U.}$$

$$X_{T_1}^{+} = \frac{V_1^{+}(F) - V_S^{+}(F)}{X_{T_1}^{+}} = \frac{0.765 - 0.637}{j0.02} = -j6.4 \text{ P.U.}$$

$$X_{T_1}^{-} = \frac{V_1^{-}(F) - V_S^{-}(F)}{X_{T_1}^{-}} = \frac{(-0.284)-(-0.412)}{j0.02} = -j6.4 \text{ P.U.}$$

@ I_{T_1} Phase

$$\begin{bmatrix} I_{T_1}^{a} \\ I_{T_1}^{b} \\ I_{T_1}^{c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{T_1}^{0} = -j12.2 \\ I_{T_1}^{+} = -j6.4 \\ I_{T_1}^{-} = -j6.4 \end{bmatrix}$$

$$\begin{bmatrix} I_{T_1}^{0} \\ I_{T_1}^{+} \\ I_{T_1}^{-} \end{bmatrix} = \begin{bmatrix} -j25 \text{ P.U.} \\ -j5.8 \text{ P.U.} \\ -j5.8 \text{ P.U.} \end{bmatrix}$$

g) Use the data given in Tables 1-3 to modify the five-bus power system that you built in PowerWorld Simulator for Simulation Project #1. Use the modified system to confirm the results of parts d, e, and f. Take screenshots of the dialog boxes and paste them here. (30 Points)

Figure Q.1 - Power World Simulation Phase Component of Single Line to Ground Fault Per Unit Current at Bus 1

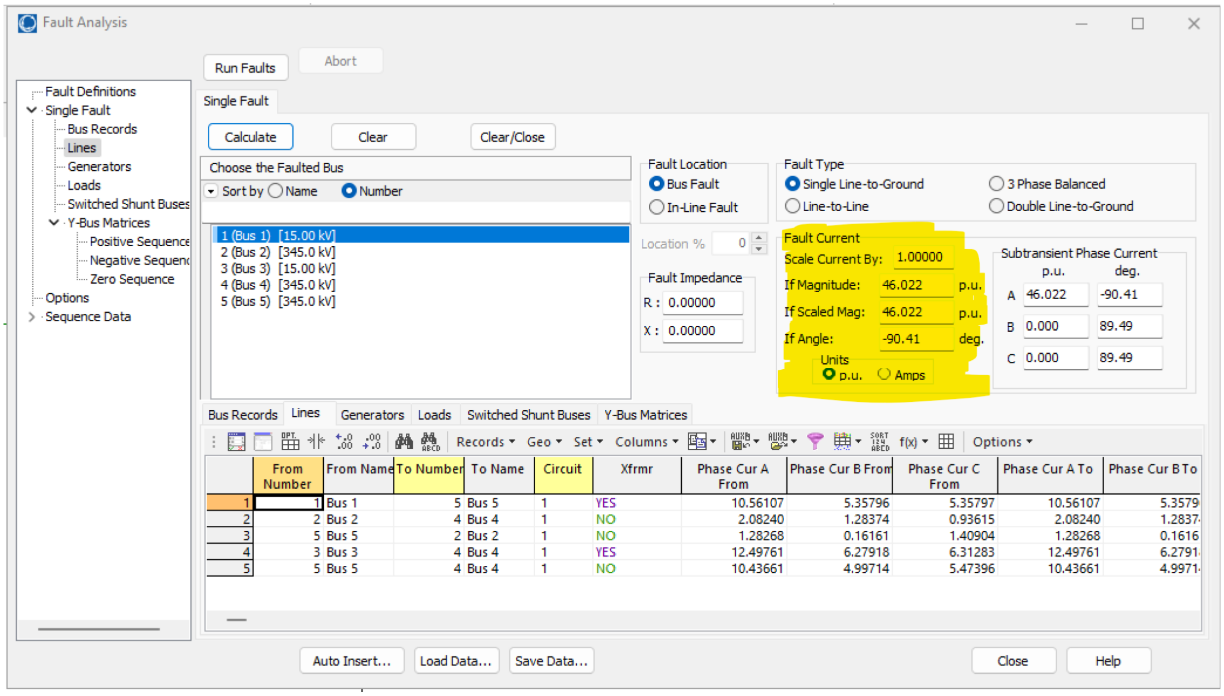


Figure Q.2 - Power World Simulation Phase Component of Single Line to Ground Fault Per Unit Current at Bus 2

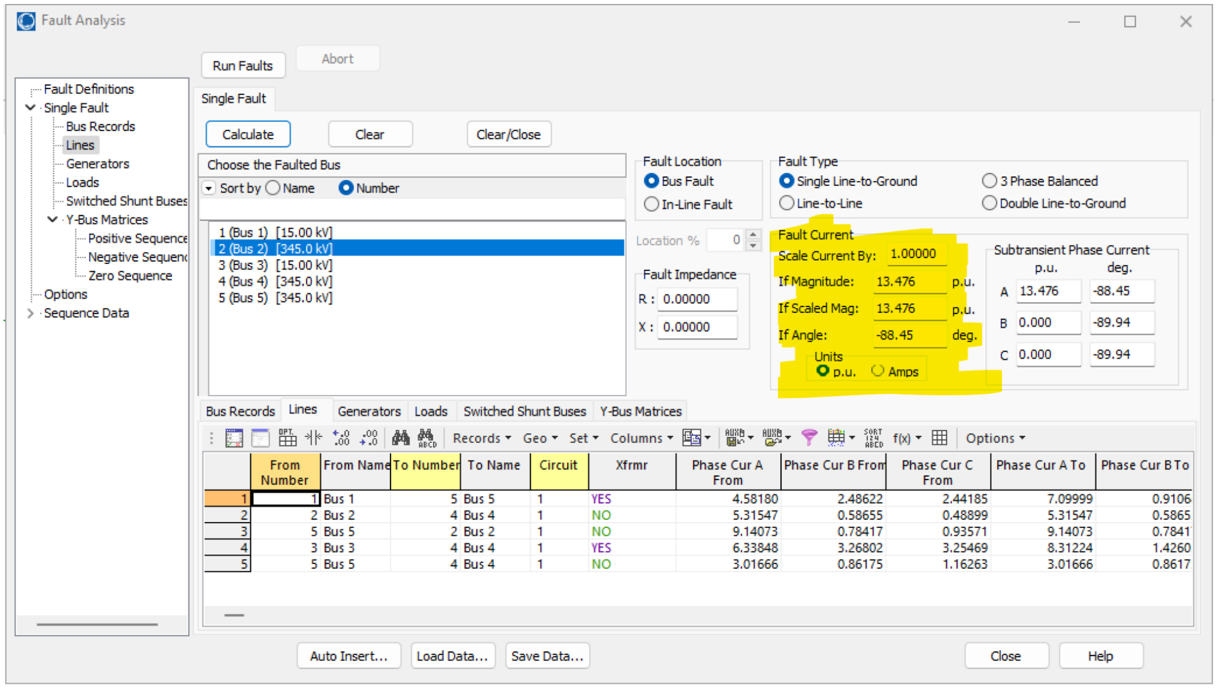


Figure Q.3 - Power World Simulation Phase Component of Single Line to Ground Fault Per Unit Current at Bus 3

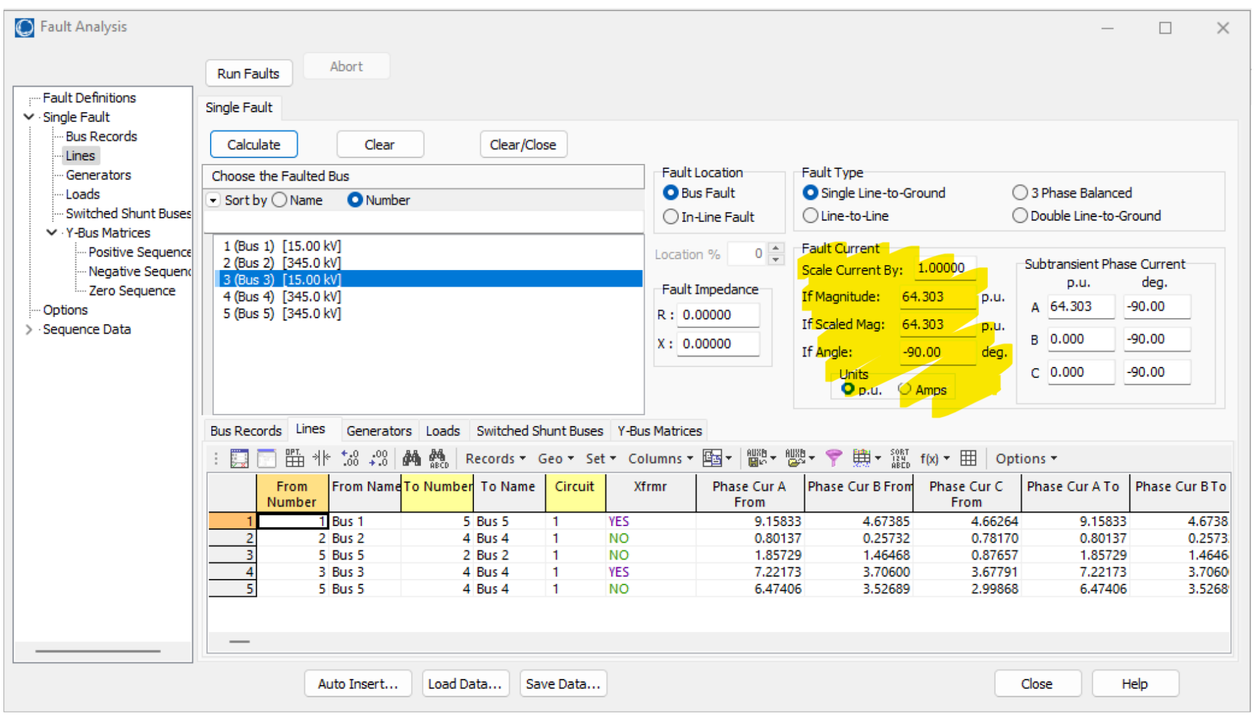


Figure Q.4 - Power World Simulation Phase Component of Single Line to Ground Fault Per Unit Current at Bus 4

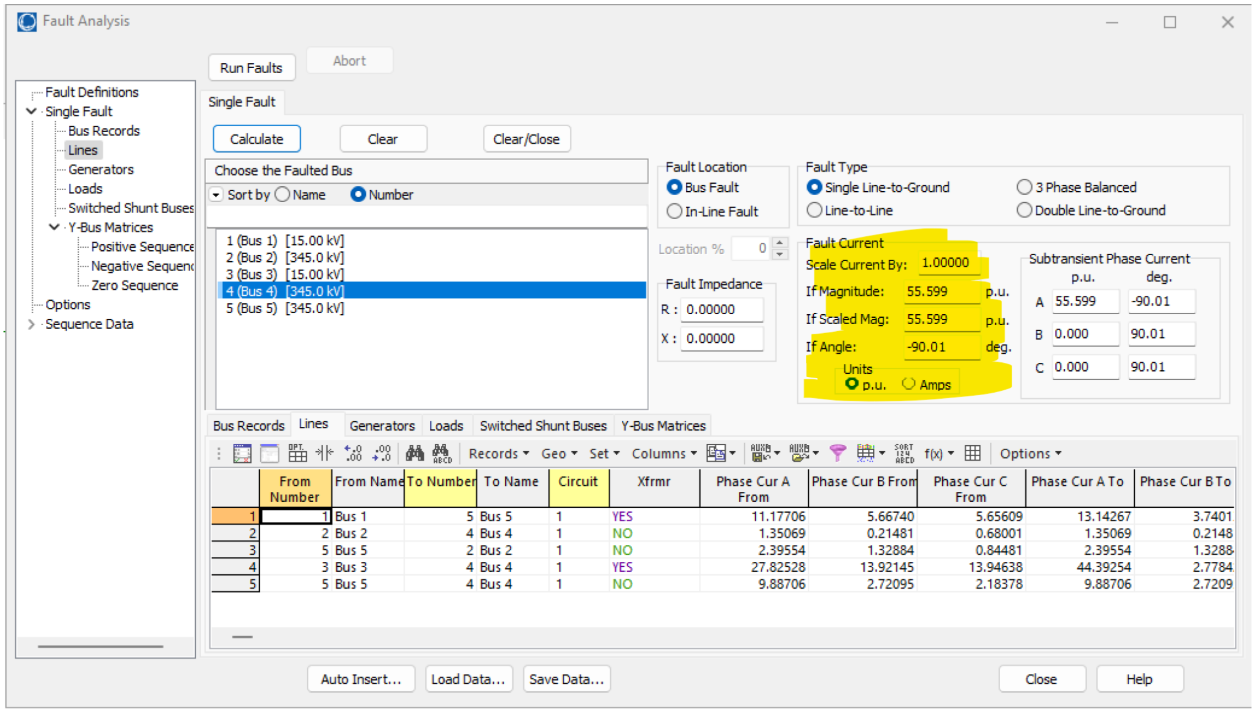


Figure Q.5 - Power World Simulation Phase Component of Single Line to Ground Fault Per Unit Current at Bus 5

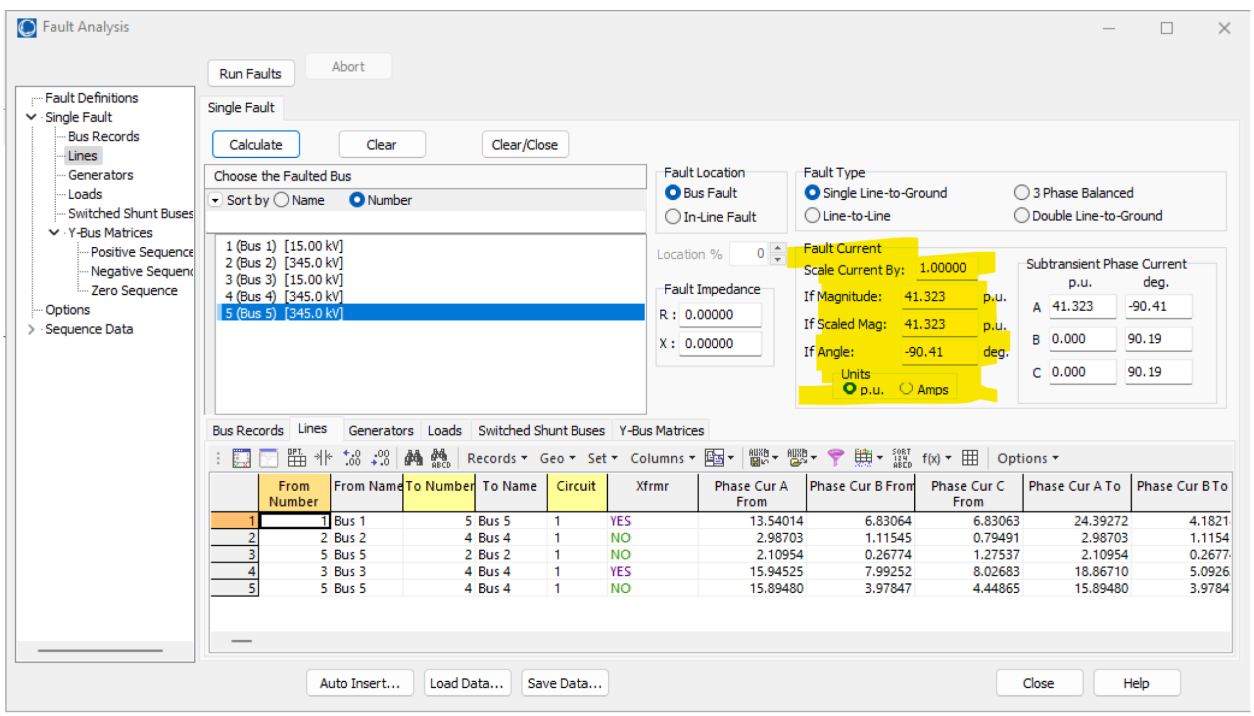


Figure E.1 - Power World Simulation Phase Component of per-unit sequence bus voltages during fault at bus 1

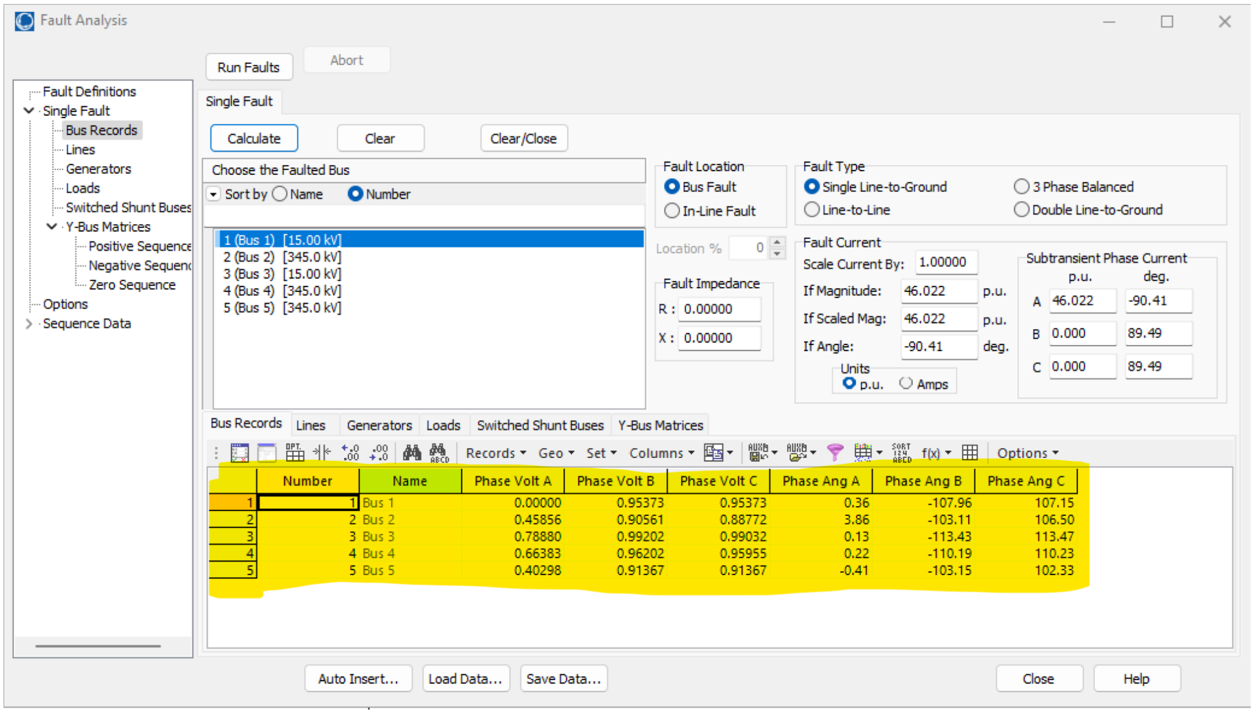


Figure E.2 - Power World Simulation Phase Component of per-unit sequence bus voltages during fault at bus 2

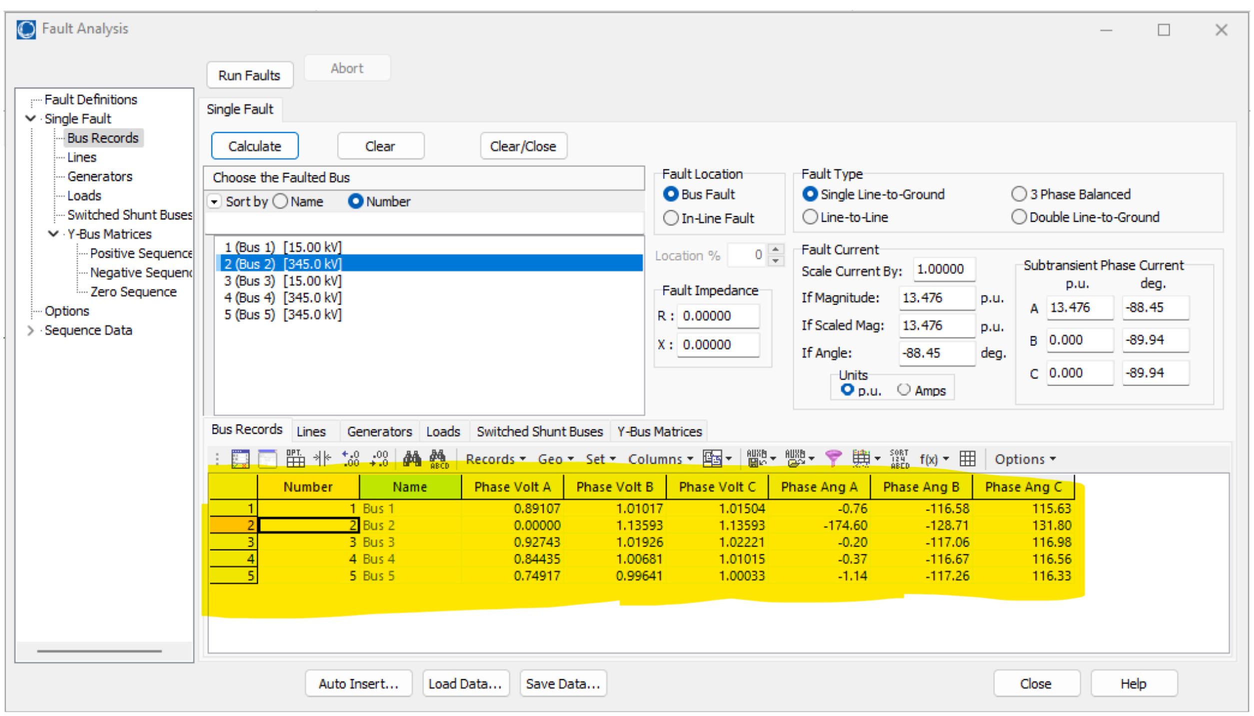
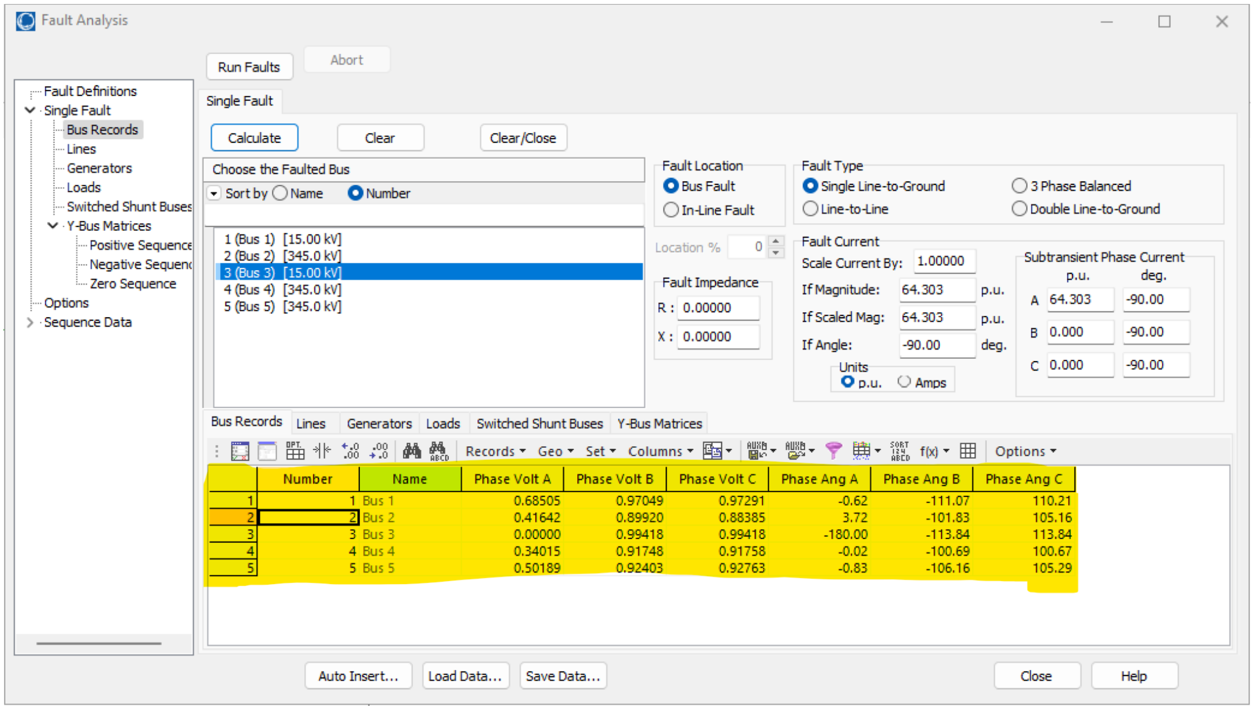
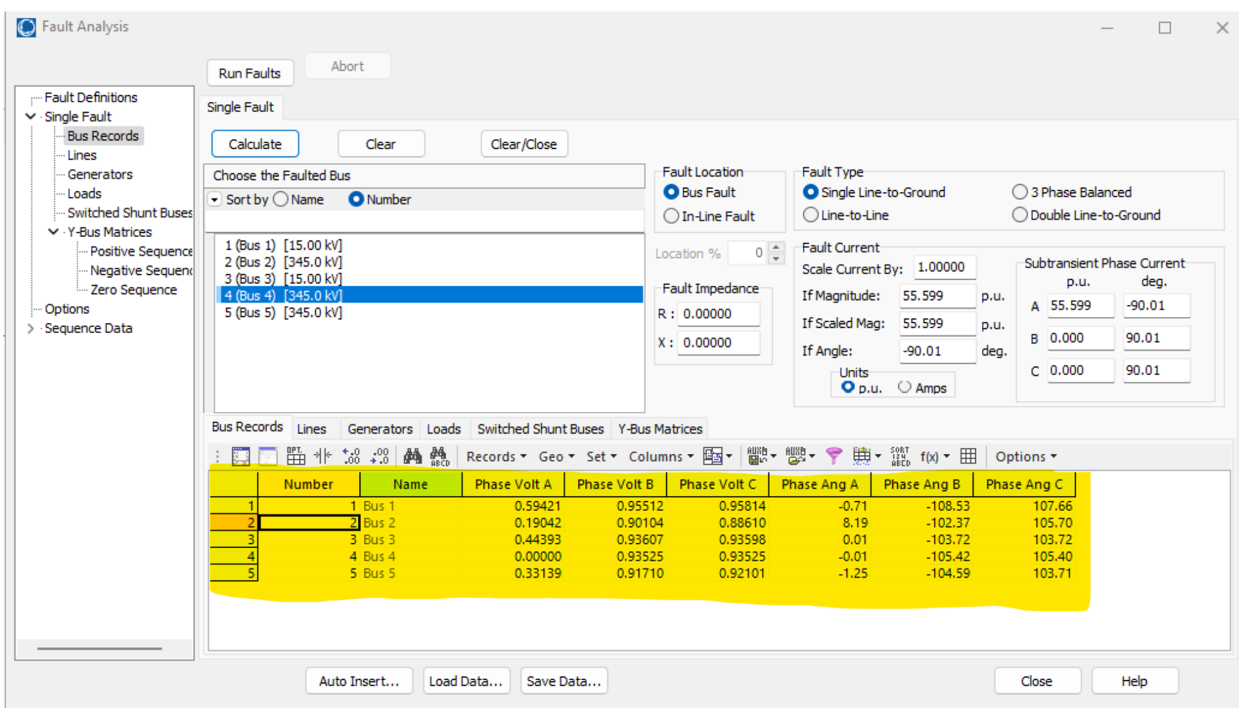


Figure E.3 - Power World Simulation Phase Component of per-unit sequence bus voltages during fault at bus 3



	Number	Name	Phase Volt A	Phase Volt B	Phase Volt C	Phase Ang A	Phase Ang B	Phase Ang C
1	1	Bus 1	0.68505	0.97049	0.97291	-0.62	-111.07	110.21
2	2	Bus 2	0.41642	0.89920	0.88385	3.72	-101.83	105.16
3	3	Bus 3	0.00000	0.99418	0.99418	-180.00	-113.84	113.84
4	4	Bus 4	0.34015	0.91748	0.91758	-0.02	-100.69	100.67
5	5	Bus 5	0.50189	0.92403	0.92763	-0.83	-106.16	105.29

Figure E.4 - Power World Simulation Phase Component of per-unit sequence bus voltages during fault at bus 4



	Number	Name	Phase Volt A	Phase Volt B	Phase Volt C	Phase Ang A	Phase Ang B	Phase Ang C
1	1	Bus 1	0.59421	0.95512	0.95814	-0.71	-108.53	107.66
2	2	Bus 2	0.19042	0.90104	0.88610	8.19	-102.37	105.70
3	3	Bus 3	0.44393	0.93607	0.93598	0.01	-103.72	103.72
4	4	Bus 4	0.00000	0.93525	0.93525	-0.01	-105.42	105.40
5	5	Bus 5	0.33139	0.91710	0.92101	-1.25	-104.59	103.71

Figure E.5 - Power World Simulation Phase Component of per-unit sequence bus voltages during fault at bus 5

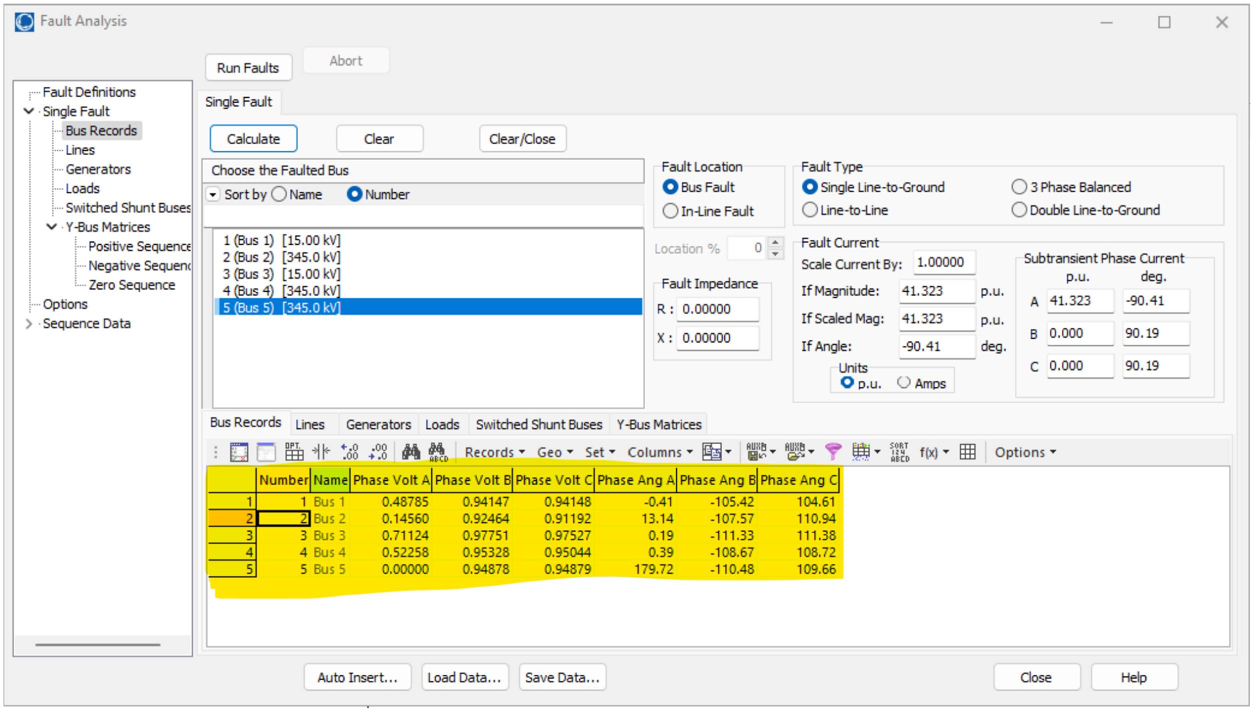


Figure F.1.1 - Power World Simulation Sequence components of the fault current contributions from Generator 1 for the fault at bus 1.

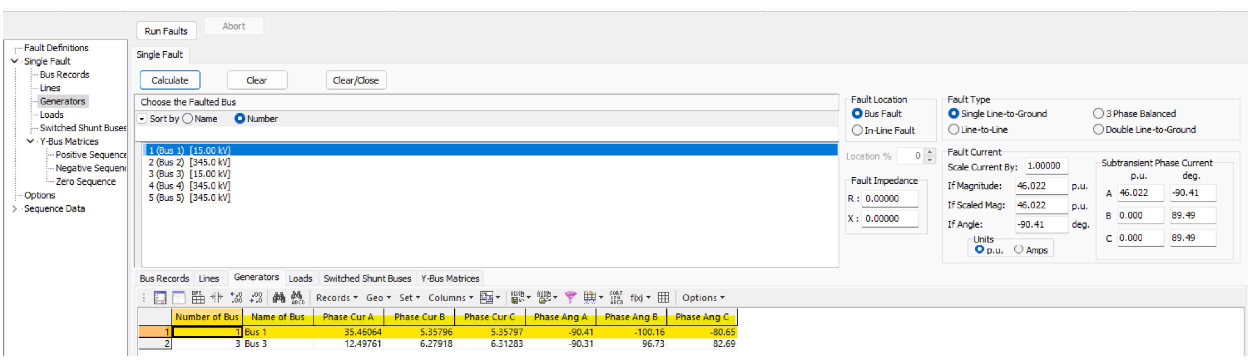


Figure F.1.2 - Power World Simulation Sequence components of the fault current contributions from Transformer 1 for the fault at bus 1.

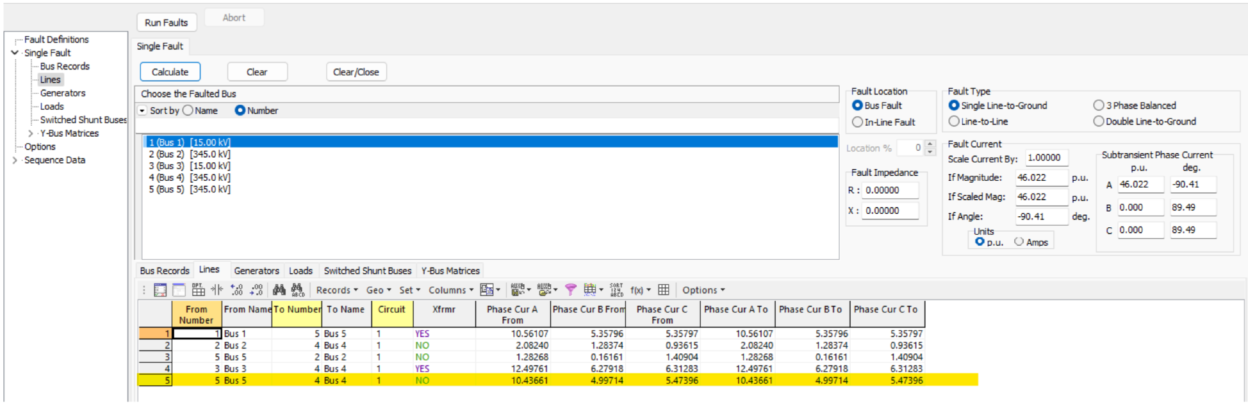


Figure F.2.1 - Power World Simulation Sequence components of the fault current contributions from Line 1 and Line 2 for the fault at bus 2.

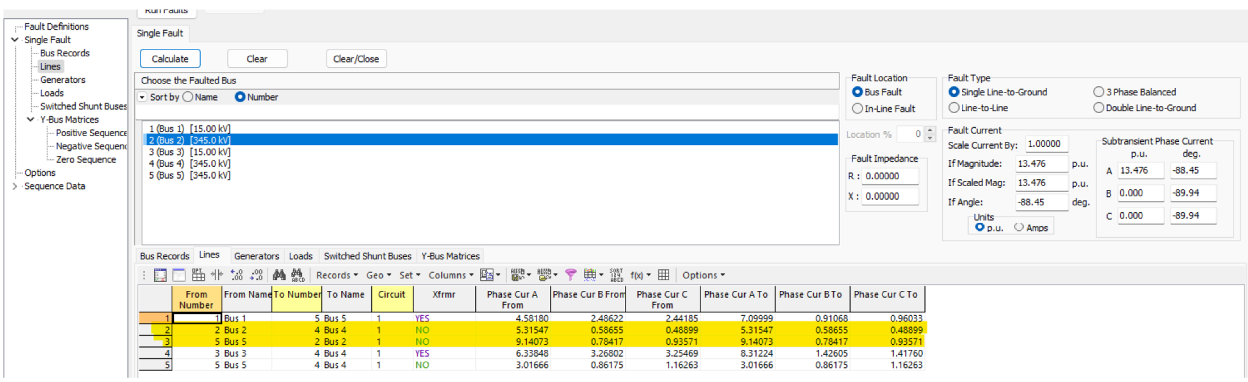


Figure F.3.1 - Power World Simulation Sequence components of the fault current contributions from Generator 2 for the fault at bus 3.

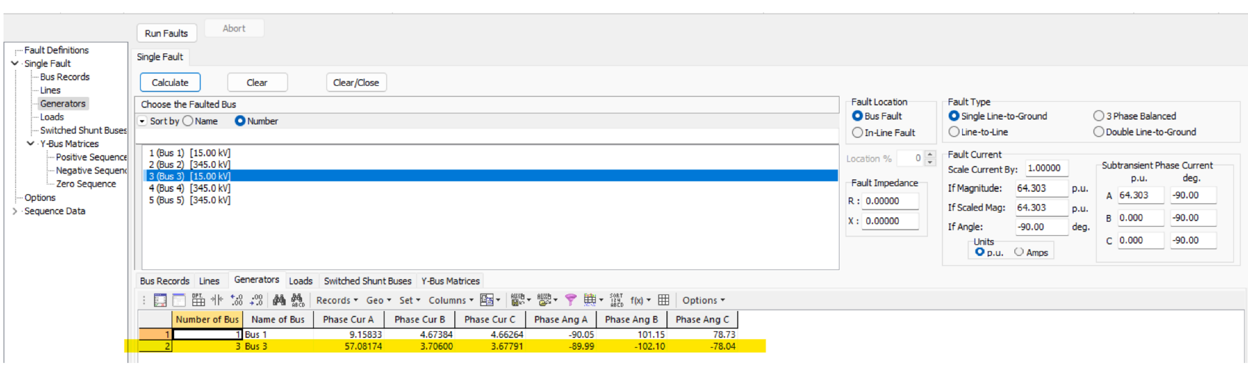


Figure F.3.2 - Power World Simulation Sequence components of the fault current contributions from Transformer 2 for the fault at bus 3.

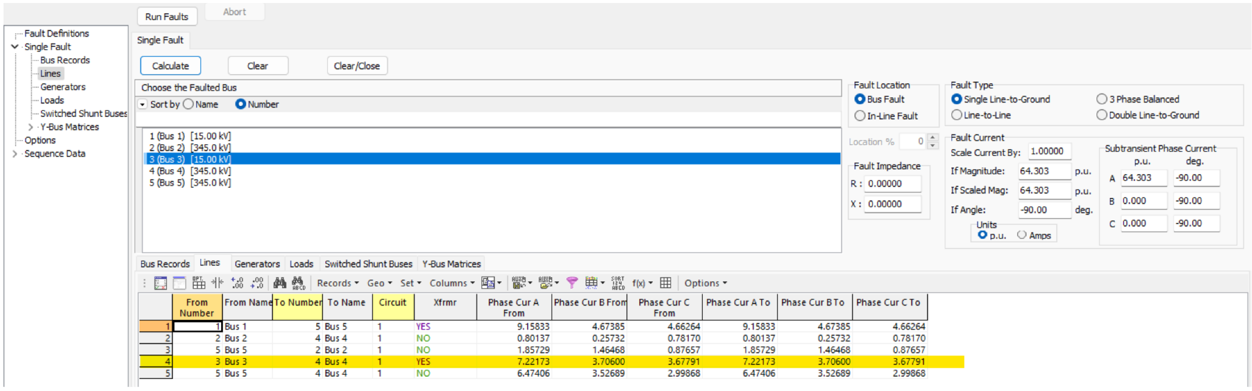


Figure F.4.1 - Power World Simulation Sequence components of the fault current contributions from Line 1 and Line 2 for the fault at bus 4.

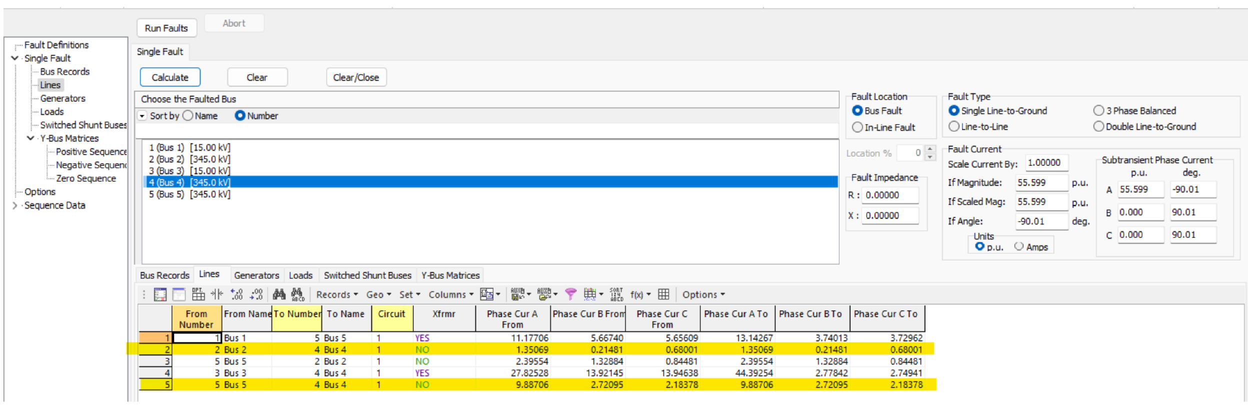


Figure F.4.3 - Power World Simulation Sequence components of the fault current contributions from Transformer 2 for the fault at bus 4.

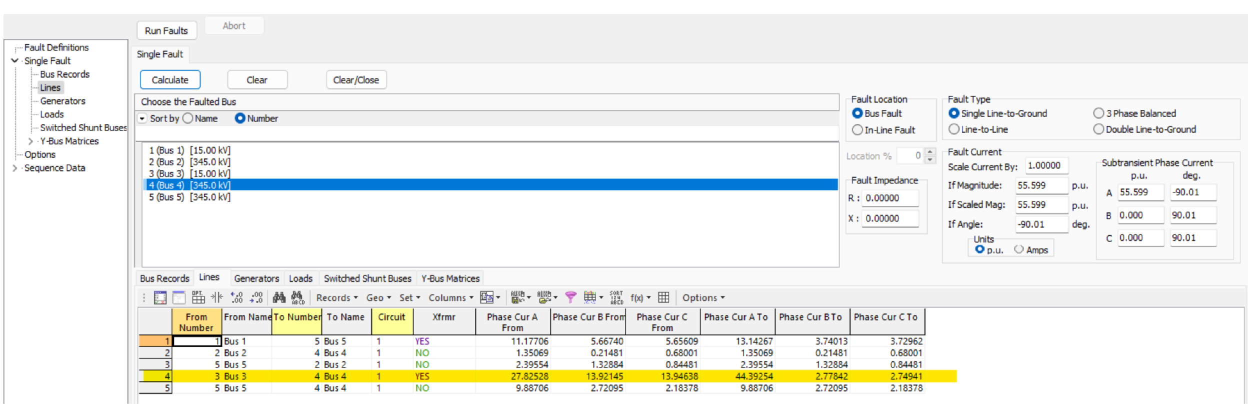
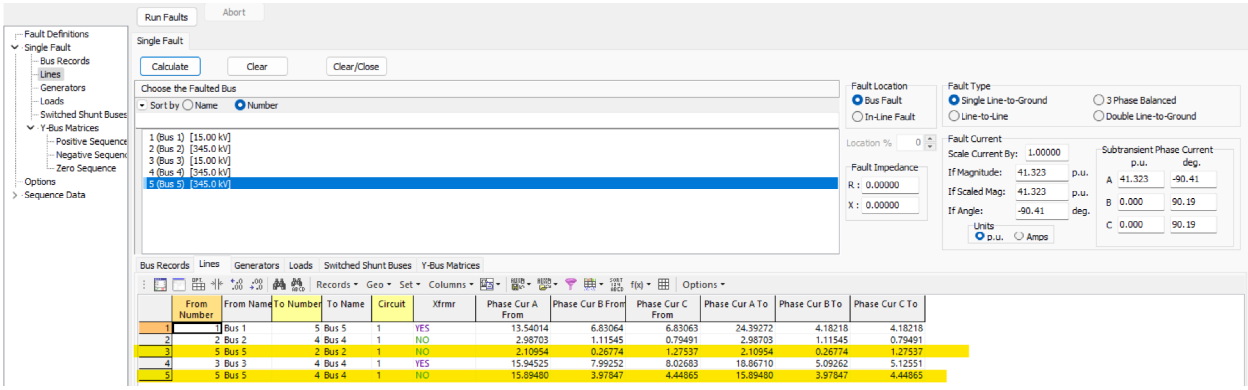
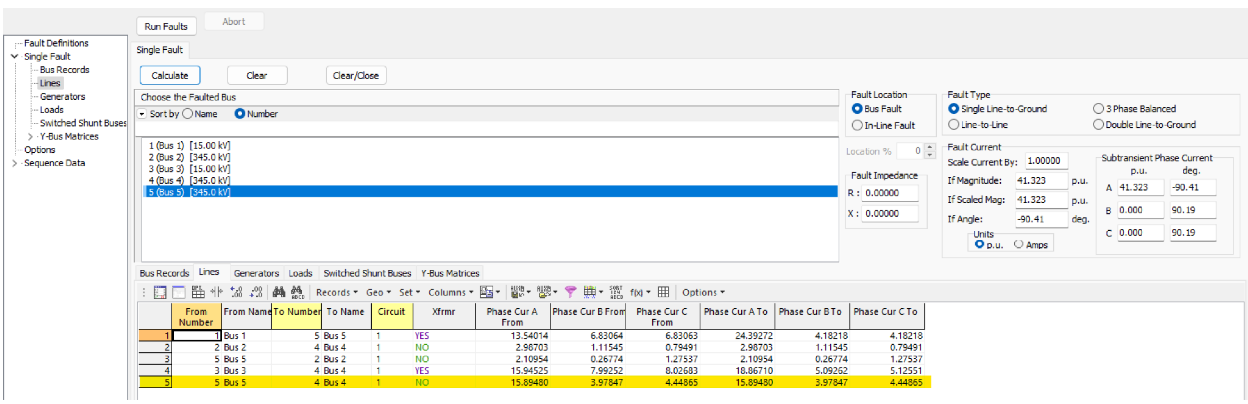


Figure F.5.1 - Power World Simulation Sequence components of the fault current contributions from Line 2 and Line 3 for the fault at bus 5.



	From Number	From Name	To Number	To Name	Circuit	Xfrmr	Phase Cur A From	Phase Cur B From	Phase Cur C From	Phase Cur A To	Phase Cur B To	Phase Cur C To
1	1	Bus 1	5	Bus 5	1	YES	13.54014	6.83064	6.83063	24.39272	4.18218	4.18218
2	2	Bus 2	4	Bus 4	1	NO	2.98703	1.11545	0.79491	2.98703	1.11545	0.79491
3	5	Bus 5	2	Bus 2	1	NO	2.10954	0.26774	1.27537	2.10954	0.26774	1.27537
4	3	Bus 3	4	Bus 4	1	YES	15.94525	7.99252	8.02683	18.86710	5.09262	5.12551
5	5	Bus 5	4	Bus 4	1	NO	15.89480	3.97847	4.44865	15.89480	3.97847	4.44865

Figure F.5.3 - Power World Simulation Sequence components of the fault current contributions from Transformer 1 for the fault at bus 5.



	From Number	From Name	To Number	To Name	Circuit	Xfrmr	Phase Cur A From	Phase Cur B From	Phase Cur C From	Phase Cur A To	Phase Cur B To	Phase Cur C To
1	1	Bus 1	5	Bus 5	1	YES	13.54014	6.83064	6.83063	24.39272	4.18218	4.18218
2	2	Bus 2	4	Bus 4	1	NO	2.98703	1.11545	0.79491	2.98703	1.11545	0.79491
3	5	Bus 5	2	Bus 2	1	NO	2.10954	0.26774	1.27537	2.10954	0.26774	1.27537
4	3	Bus 3	4	Bus 4	1	YES	15.94525	7.99252	8.02683	18.86710	5.09262	5.12551
5	5	Bus 5	4	Bus 4	1	NO	15.89480	3.97847	4.44865	15.89480	3.97847	4.44865

Appendix:

Fault Bus	Single Line-to-Ground Fault Current (Phase A) per unit/degrees	Contributions to Fault Current				
		GEN LINE OR TRSF	Bus-to-Bus	Phase A	Current Phase B	Phase C
				per unit/degrees		
1	46.02/−90.00	G1	GRND–1	34.41/ −90.00	5.804/ −90.00	5.804/ −90.00
		T1	5–1	11.61/ −90.00	5.804/ 90.00	5.804/ 90.00
2	14.14/−90.00	L1	4–2	5.151/ −90.00	0.1124/ 90.00	0.1124/ 90.00
		L2	5–2	8.984/ −90.00	0.1124/ −90.00	0.1124/ −90.00
3	64.30/−90.00	G2	GRND–3	56.19/ −90.00	4.055/ −90.00	4.055/ −90.00
		T2	4–3	8.110/ −90.00	4.055/ 90.00	4.055/ 90.00
4	56.07/−90.00	L1	2–4	1.742/ −90.00	0.4464/ 90.00	0.4464/ 90.00
		L3	5–4	10.46/ −90.00	2.679/ 90.00	2.679/ 90.00
		T2	3–4	43.88/ −90.00	3.125/ −90.00	3.125/ −90.00
5	42.16/−90.00	L2	2–5	2.621/ −90.00	0.6716/ 90.00	0.6716/ 90.00
		L3	4–5	15.72/ −90.00	4.029/ 90.00	4.029/ 90.00
		T1	1–5	23.82/ −90.00	4.700/ −90.00	4.700/ −90.00

$V_{prefault} = 1.05 \angle 0$		Bus Voltages during Fault		
Fault Bus	Bus	Phase A	Phase B	Phase C
1	1	$0.0000 \angle 0.00$	$0.9537 \angle -107.55$	$0.9537 \angle 107.55$
	2	$0.5069 \angle 0.00$	$0.9440 \angle -105.57$	$0.9440 \angle 105.57$
	3	$0.7888 \angle 0.00$	$0.9912 \angle -113.45$	$0.9912 \angle 113.45$
	4	$0.6727 \angle 0.00$	$0.9695 \angle -110.30$	$0.9695 \angle 110.30$
	5	$0.4239 \angle 0.00$	$0.9337 \angle -103.12$	$0.9337 \angle 103.12$
2	1	$0.8832 \angle 0.00$	$1.0109 \angle -115.90$	$1.0109 \angle 115.90$
	2	$0.0000 \angle 0.00$	$1.1915 \angle -130.26$	$1.1915 \angle 130.26$
	3	$0.9214 \angle 0.00$	$1.0194 \angle -116.87$	$1.0194 \angle 116.87$
	4	$0.8435 \angle 0.00$	$1.0158 \angle -116.47$	$1.0158 \angle 116.47$
	5	$0.7562 \angle 0.00$	$1.0179 \angle -116.70$	$1.0179 \angle 116.70$
3	1	$0.6851 \angle 0.00$	$0.9717 \angle -110.64$	$0.9717 \angle 110.64$
	2	$0.4649 \angle 0.00$	$0.9386 \angle -104.34$	$0.9386 \angle 104.34$
	3	$0.0000 \angle 0.00$	$0.9942 \angle -113.84$	$0.9942 \angle 113.84$
	4	$0.3490 \angle 0.00$	$0.9259 \angle -100.86$	$0.9259 \angle 100.86$
	5	$0.5228 \angle 0.00$	$0.9462 \angle -106.04$	$0.9462 \angle 106.04$
4	1	$0.5903 \angle 0.00$	$0.9560 \angle -107.98$	$0.9560 \angle 107.98$
	2	$0.2309 \angle 0.00$	$0.9401 \angle -104.70$	$0.9401 \angle 104.70$
	3	$0.4387 \angle 0.00$	$0.9354 \angle -103.56$	$0.9354 \angle 103.56$
	4	$0.0000 \angle 0.00$	$0.9432 \angle -105.41$	$0.9432 \angle 105.41$
	5	$0.3463 \angle 0.00$	$0.9386 \angle -104.35$	$0.9386 \angle 104.35$
5	1	$0.4764 \angle 0.00$	$0.9400 \angle -104.68$	$0.9400 \angle 104.68$
	2	$0.1736 \angle 0.00$	$0.9651 \angle -109.57$	$0.9651 \angle 109.57$
	3	$0.7043 \angle 0.00$	$0.9751 \angle -111.17$	$0.9751 \angle 111.17$
	4	$0.5209 \angle 0.00$	$0.9592 \angle -108.55$	$0.9592 \angle 108.55$
	5	$0.0000 \angle 0.00$	$0.9681 \angle -110.07$	$0.9681 \angle 110.07$